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Veileder: Ph.D. Student Lene Eliassen	
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Summary

In this master thesis analyses will be conducted on a 5MW offshore wind turbine, with a jacket foundation. The goal is to investigate how seven different wind profiles affect fatigue in the blade root, the tower top and the tower bottom. The effect of the turbulence level is also investigated. The analyses examine how the fatigue loads differs from one wind profile to the next, which means it is actually the relative fatigue that is being calculated.

There are a total of seven wind profiles investigated, based on the logarithmic wind profile formula. Due to limitations in the software used, power law wind profiles are used in the analysis. The seven wind profiles have different shear, but the differences are small. Calculations have been made to determine which wind profile that is expected to cause the greatest damage. For each wind profiles the turbulence intensity (TI) is changed from 25 % to 11 % to 0 %, to investigate how this will impact. By including turbulence one gets wind fields. The wind fields are simulated by the software application Turbsim.

The wind fields cause different load impact. The loads are calculated by the multi-body software called Fedem Windpower. The loads are then post-processed by Mlife, which is a MatLab application, in order to obtain damage equivalent load (DEL), i.e. relative fatigue.

The DEL's are tabulated in the result chapter for the 18 load conditions analyzed, where the turbulence is reduced from 25 % to 11 % to 0 %. All the DEL's are normalized with respect to the neutral wind profile. Additionally, the result chapter shows graphically the normalized values for selected loads.

DEL caused by the bending moment out of plane (RMy) is considered most significant to investigate which of the wind profiles that are causing the highest DEL. The result chapter shows DEL results caused by RMy that are not as expected when turbulence is included. In the discussion chapter this case is widely discussed. It appears that the reason has to do with the fact that the mean turbulence variation on both sides of one wind profile is larger than the difference between the wind profiles. Since the turbulence simulation is random and the difference between the wind profiles is small, the mean value variation due to random turbulence can be larger than the variation between any of the seven wind profiles. For this reason it is difficult to draw any conclusion when turbulence is included. If however, the turbulence is ignored, the expected results are achieved.

Conclusion:

- No turbulence; the expected results are achieved
- Turbulence included; no clear results

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1 Introduction

In recent years there has been an increased interest on renewable energy, by government's organizations and individuals. The motivation for this engagement is due to a number of reasons. One of these reasons is to reduce emissions of greenhouse gases, thereby reducing the impact that this has on the environment. Another motivation is to become independent of foreign oil, because of political instability in oil exporting countries. A third motivation is that the world is hungry for energy, and by meeting this need, an increasing number of people will be lifted out of poverty.

The commitment to renewable energy spans over a wide specter of energy sources. This includes solar energy, wave energy and wind energy etc. Among these, wind energy is an important one. Therefore there has been done a lot of research for the last decades, to improve wind turbines, including offshore wind turbine. This research involves making wind turbines more efficient for electricity production, more cost efficient, to handle more fatigue etc.

Wind turbines in general and offshore wind turbines in particular, have a huge development potential. This is due to large unused regions. This is especially true at offshore locations, in which conflicts are less due to noise and visual esthetics. In addition, offshore wind turbines are exposed to greater wind influences than the case is with land-based wind turbines. This is due to no obstacles, such as mountains and buildings. On the other hand it is more difficult to perform maintenance at offshore locations.

A major research project taking place these days is called OC4. This is a research project taking place across national borders. The abbreviation OC4 stands for Offshore Code Comparison Collaboration Continuation. The goal for OC4 is to develop dynamic computer codes to simulate and assess wind turbines and support structures, and compare these codes to design models. This research project is an ongoing project, and still many questions are unanswered. [1]

This thesis is focusing on the wind turbine model used in the OC4 project; the NREL offshore 5-MW baseline wind turbine. The main goal for the thesis is to provide results for how seven different wind profiles affect the fatigue on the wind turbine.

2 Theory

2.1 Wind profiles

The wind speed profile is a representation of a mean wind speed that varies with height above the sea surface. In the absence of complex stability and terrain conditions, idealized models are used for this representation. In DNV-RP-C205 (2010) there are three examples of such idealized models. They are the logarithmic wind profile model, the power law wind profile model and the Frøya wind profile model. Of these, the models most widely applied are the logarithmic and power law wind profile. These will be described in the following sections. The Frøya wind profile model will not be dealt with in this thesis. [2]

2.1.1 Logarithmic wind profile

From the reference level the wind speed profile can be calculated at any level by using the logarithmic wind profile based on neutral atmospheric conditions. This can be written as in formula 2.1. [2]

$$U(\mathrm{z}) = U(H)\left(\frac{ln\frac{z}{z_0}}{ln\frac{H}{z_0}}\right) \qquad \mathbf{2.1}$$

Here U (H) is the reference speed, and z is a variable which denote the height from still water level. The abbreviation z_0 denotes the roughness length. [2]

The roughness length parameter is in offshore location a parameter that depends on wind speed, upstream distance to land, water depth and wave field. This parameter can be found implicit by formula 2.2. The procedure is to insert a value for z_0, and continue to do so until both sides are equal. This is called to perform iteration. [2]

$$z_0 = \frac{A_c}{g}\left(\frac{k_a U(z)}{\ln z/z_0}\right)^2 \qquad \mathbf{2.2}$$

In formula 2.2 A_c is a constant called Charnock's constant and has a value between 0.011-0.014 in open sea with fully developed waves. However, as one approaches the coast, this value can be 0.018 or more. The abbreviation g represents the gravity, and k_a is the Karman's constant with value 0.4. [2]

Finally when this parameter has been found, it is possible to calculate the neutral logarithmic wind profile by formula 2.1. [2]

2.1.2 Atmospheric stability

In order to take into consideration the atmospheric stability condition, formula 2.1 has to be modified by a stability correction parameter ψ. Then the formula will be as follows: [3] [4]

$$U(Z) = U(H)\frac{\ln\frac{Z}{Z_0} - \psi}{\ln\frac{H}{Z_0} - \psi} \qquad \textbf{2.3}$$

As mentioned in the previous section, formula 2.1 is based on an atmospheric stability which is neutral. This neutral stability is the idealized model/shape. In nature however this shape is not always the best fit. One must take into account the differences in atmospheric stability. The atmospheric stability is divided into classes, determined by the Obukhov length L_{m0}. The Obukhov length represents the relative influence of mechanical and thermal forcing on the turbulence. [3]

The stability correction parameter, ψ, given in formula 2.3 depends on the ratio z/L_{m0}, and can be found by the use of formula 2.4 - 2.6. [3]

$$\psi_1 = 2\ln(1+x) + \ln(1+x^2) - 2tan^{-1}(x)\ for \frac{z}{L_{m0}} < 0 \qquad \textbf{2.4}$$

$$x = \left(1 - 19{,}3\frac{z}{L_{m0}}\right)^{\frac{1}{4}} \qquad \textbf{2.5}$$

$$\psi_2 = -4{,}8\frac{z}{L_{m0}}\ for \frac{z}{L_{m0}} \geq 0 \qquad \textbf{2.6}$$

2.1.3 Power law wind profile

The power law wind profile is an alternative way to calculate wind speed at different heights, and is calculated by formula 2.7. [2]

$$U(Z) = U(H)\left(\frac{Z}{H}\right)^{\alpha} \qquad \textbf{2.7}$$

2.2 Turbulence

The turbulence intensity can be calculated by using formula 2.8.

$$T = \frac{\sigma_U}{U(H)} \quad \textbf{2.8}$$

[5]

, where T is turbulence intensity, σ_U is standard deviation, U(H) is mean wind speed at reference height (11.4 m/s). [5]

$$\sigma_U = \frac{U(H)}{ln\left(\frac{H}{z_0}\right)} + 1.28 \cdot 1.44 \cdot I_{15}, where\ I_{15} = 0.14\ (medium\ turbulence) \quad \textbf{2.9}$$

[6] [7]

2.3 Wind field and grid

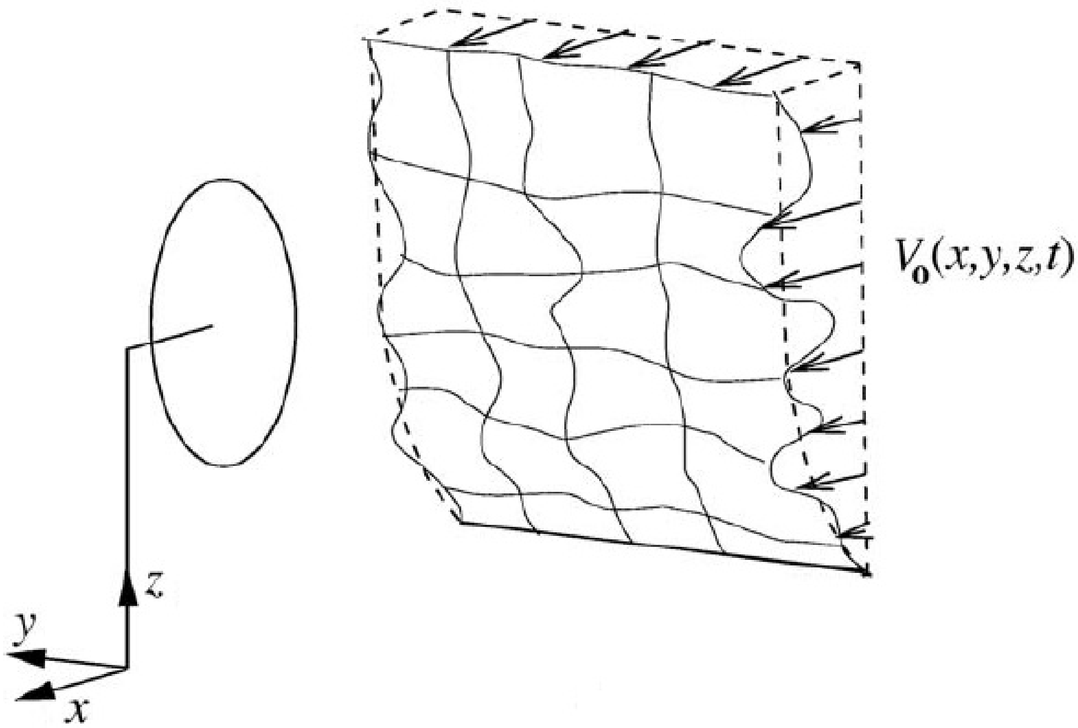


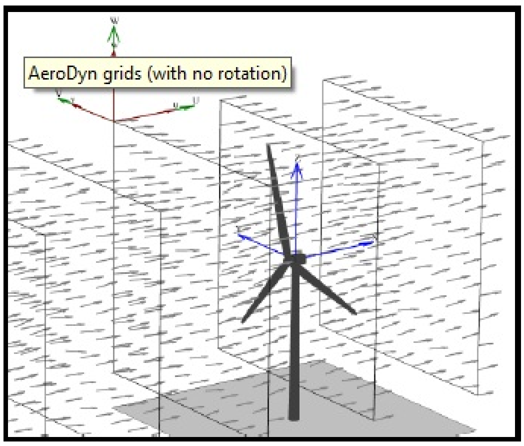
Figure 2.1 Wind field illustration [8]

Figure 2.1 illustrates a wind field. This wind field is bounded by a height and a width, called grid height and grid width. Further, the dashed lines which is bended, represents a wind profile if no turbulence is present. They are constant during the simulation. If one instead takes into account turbulence, the distorted lines represent the wind velocity. These lines represent the velocity at a given time. [8]

2.4 Turbsim

Turbsim is a software application used to generate wind fields. A wind field consists of wind profile and turbulence. In turbsim the logarithmic wind profile and the power law wind profile can be selected. [9]

The application uses a statistical model to generate time series of wind fields. An illustration of how wind fields changes with time is given by Figure 2.2. [9]



[10] **Figure 2.2 Wind field crossings**

2.5 Coordinate axes

In order to describe the forces acting in different on the reference wind turbine, it is necessary to establish coordinate axes. They are illustrated in Figure 2.3 below.

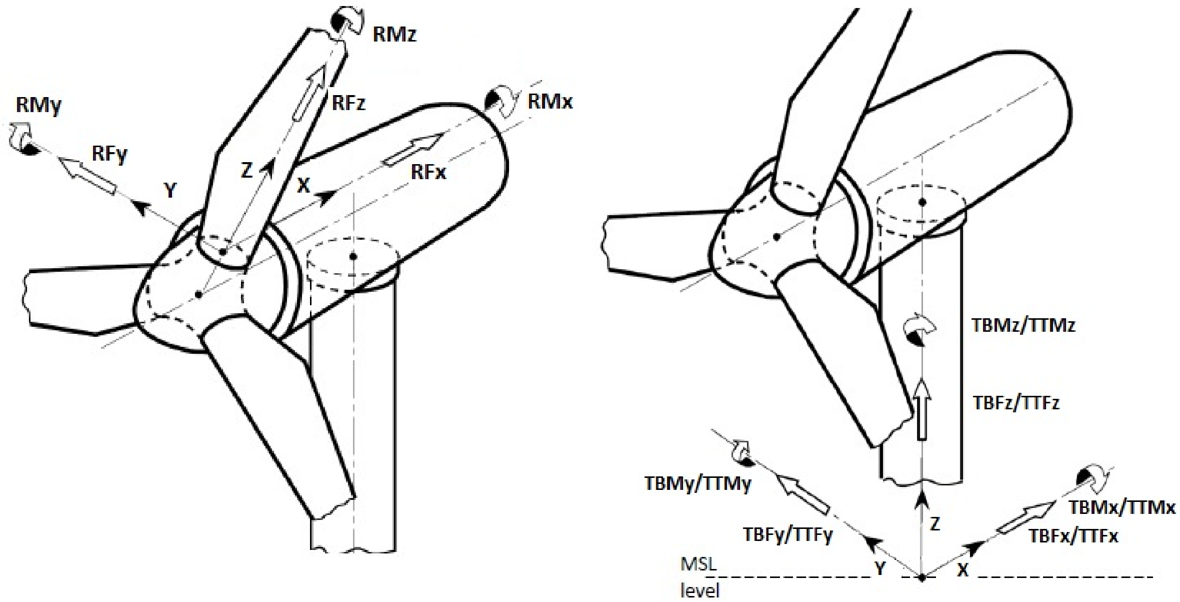


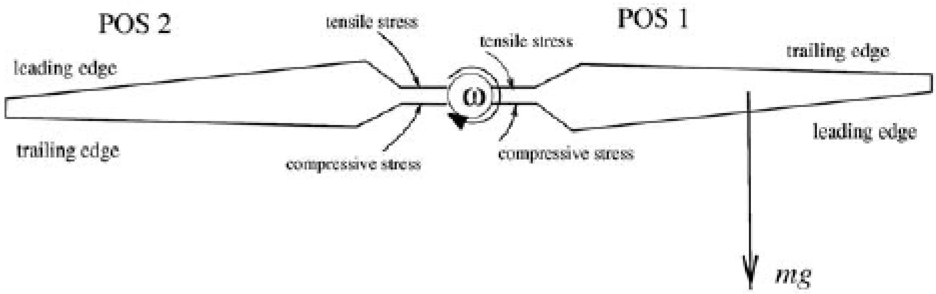
Figure 2.3 a) and b) Coordinate axes [11]

In the figure, the wind distribution which generates aerodynamic loads comes mainly from the left side. In Figure 2.3 a) the coordinate axes for the blades are illustrated. The x-axis is pointed in the downwind direction, while the z-axis starts at the blade root and ends in the blade tip. Finally the y-axis is given by the right hand Cartesian coordinate system, and pointed left in the rotor plane. The same is true for Figure 2.3 b), but here the z-axis is pointed upward. [11]

2.6 Sources of loading

2.6.1 Gravitational loading

The gravitational loading of a wind turbine can be illustrated by Figure 2.4



[13]

Figure 2.4 Gravitational sinusoidal loading

The positive y-direction in Figure 2.4 is pointed upward. The positive y-direction is illustrated in Figure 2.3. When looking at the leading edge in position 1, the blade root experience compressive stress, when exposed to gravitational load. After the turbine blade has been exposed to a half revolution, the blade root at the leading edge experience tensile stress. By being exposed to an additional half revolution, it returns to the starting point. By doing so it has finish a full cycle. Thus, the blade is exposed to a sinusoidal loading in the rotor plane due to gravity. The gravitational load provides a major contribution of the fatigue due to the large wingspan and weight. It is therefore important to take this into consideration gravitational loading. [12]

2.6.2 Aerodynamic loading

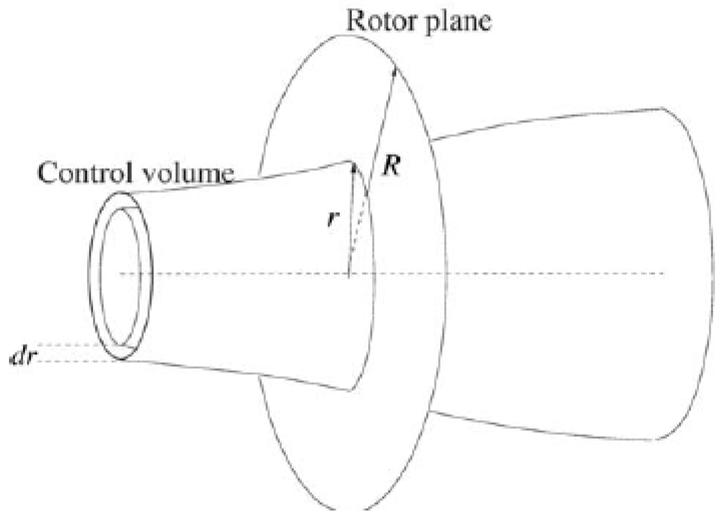
The aerodynamic loading is calculated by use of the the blade element momentum method.

2.6.2.1 The blade elementmomentum (BEM) method

The blade element momentum method can be described by use of the algorithm described in Sec.2.6.2.5. The algorithm is applied on as many control volume as a wind turbine blade is divided into. A control volume is described in Sec.2.6.2.2. When the algorithm has been performed, the local loads on each node are calculated. The local loads are then used to calculate global loads, such as bending moment and force at the blade root. [12]

2.6.2.2 Control volume

In order to use the BEM method, control volumes needs to be defined. A control volume consists of an annular element multiplied by the element length, dr. An illustration of a control volume is given in Figure 2.5 below. [12]



[14]

Figure 2.5 Control volume

Here R is rotor radius, r is radius from hub center to the specified node, dr is element length.

2.6.2.3 Calculation of relative velocity

In Figure 2.6 an aerofoil is shown, which is a cross section of a wind turbine blade. It is sliced at a node, to be used as an illustration of the wind speed acting on the wind turbine blade. The dashed line is the rotor plane. This means that the whole wind turbine is turned 90 degree such that the hub is pointed downward. [12]

The wind velocity, V_0 (1-a), is acting perpendicular to the rotor plane, while the rotational velocity, ωr (1+a'), is acting tangential. These two combined by the use of Pythagoras gives the relative velocity. [12]

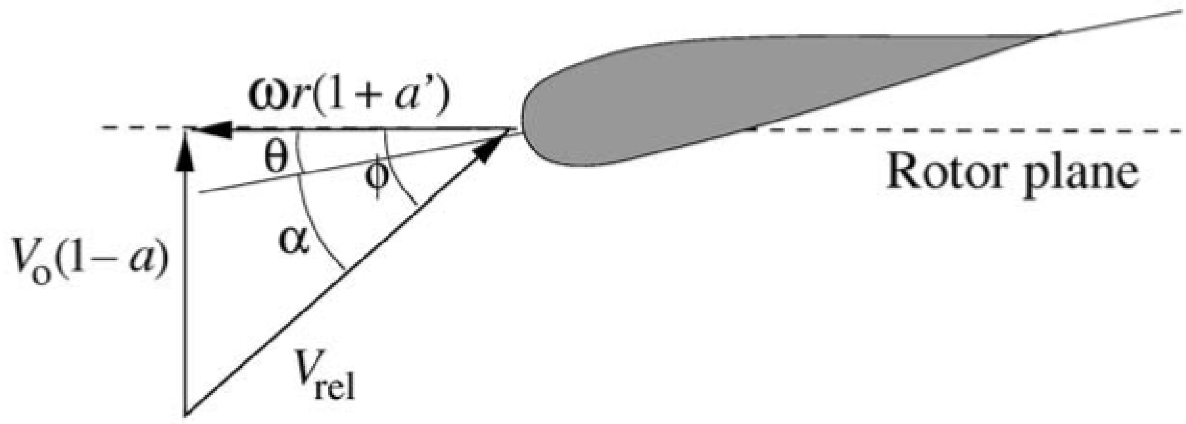


Figure 2.6 Velocities at the rotor plane [15]

Explanation of the parameters used in Figure 2.6 is tabulated in Table 2.1.

V_0	Wind speed
ω	Rotational speed
r	Radius - from hub center to the specified node
a	Axial induction factor
a'	Tangential induction factor
θ	Local pitch
ϕ	Flow angle
α	Local angle of attack

Table 2.1 Parameters used to calculate the relative velocity and angles [12]

The formula needed to calculate the relative velocity is: [12]

$$V_{rel} = \sqrt{[V_0(1-a)]^2 + [\omega r(1+a')]^2} \quad \textbf{2.10}$$

The flow angle is given by formula 2.11. [12]

$$\tan\phi = \frac{V_0(1-a)}{\omega r(1+a')} \quad \textbf{2.11}$$

The local angle of attack is given by formula 2.12: [12]

$$\alpha = \phi - \theta \quad \textbf{2.12}$$

The axial and tangential induction parameters are calculated using the BEM method. This is explained below.

2.6.2.4 *Calculation of local force at nodes*

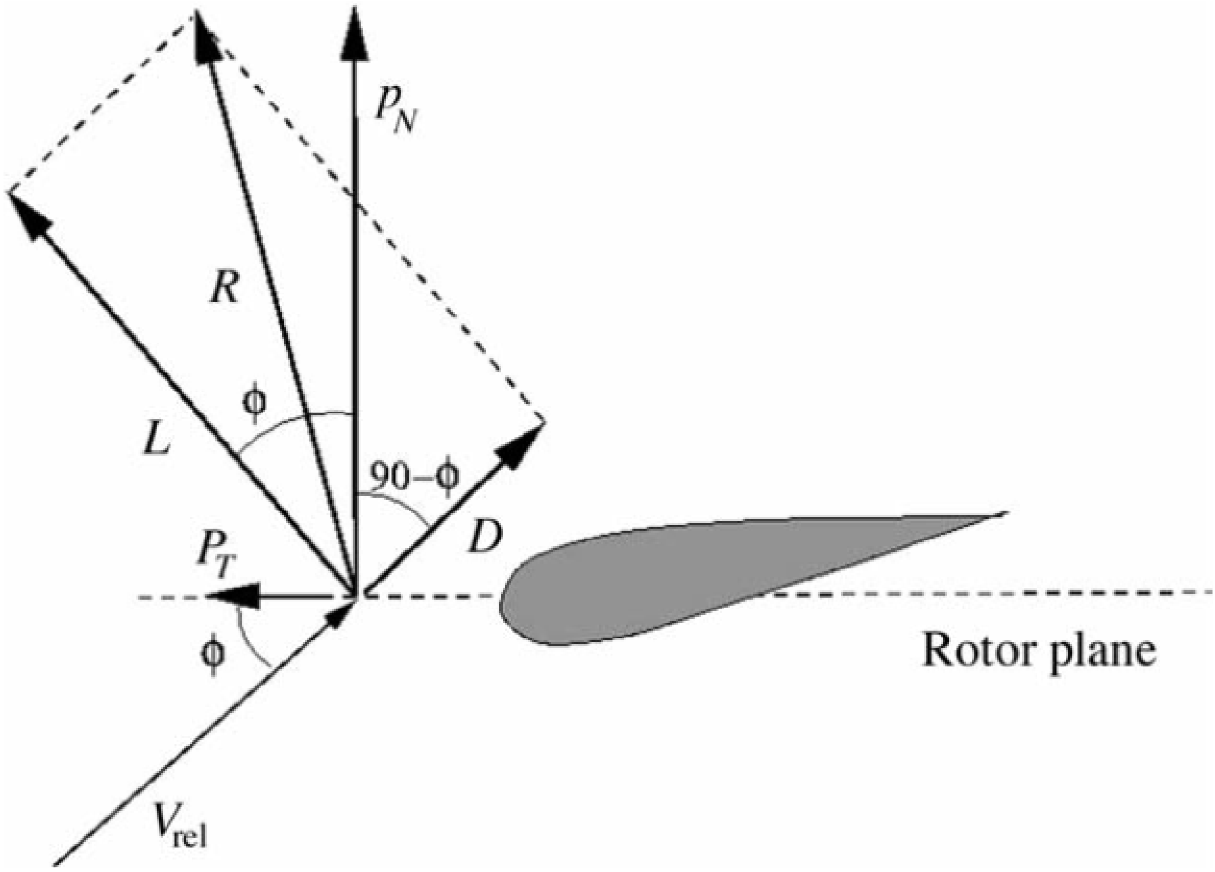


Figure 2.7 Local loads on an aerofoil, [16]

As illustrated in Figure 2.7 the forces acting on the blade element are perpendicular to each other. The force which is parallel to the relative velocity is called drag force, D, and the force which is perpendicular to the relative velocity is called lifting force, L. The vector representation in Figure 2.7 illustrate that the drag force component should be minimize in relation to the lifting force component. This is because it is the lifting force component which contributes to the revolution of the wind turbine. In order to keep the lifting force component high, the wind turbine blades is constructed with a twist from the nose of the blade to the trailing edge. To be able to calculate global loads, the local loads drag and lift, have to be projected in normal and tangential direction, relative to the rotor plane. The formulas needed to calculate the local forces at each node are given in formula 2.13 - 2.16. [12]

The lift force, L, is given by formula 2.13 [12]

$$L = \frac{1}{2}\rho V_{rel}^2 c C_l \qquad \textbf{2.13}$$

Here ρ is the air density. The letter c represents the chord length, which is the width of the blade cross section. The lift coefficient is denoted by C_l, which depends on measured values.

The drag force, D, is given by formula 2.14. [12]

$$D = \frac{1}{2}\rho V_{rel}^2 c C_d \qquad \textbf{2.14}$$

The drag coefficient is denoted by C_d, which depends on measured values.

The projected force normal to the rotor plane, P_N, is given by formula 2.15. [12]

$$P_N = L\cos\phi + D\sin\phi \qquad \textbf{2.15}$$

The projected force tangential to the rotor plane, P_T, is given by formula 2.16. [12]

$$P_T = L\sin\phi - D\cos\phi \qquad \textbf{2.16}$$

2.6.2.5 BEM algorithm

To be able to calculate the local loads the BEM algorithm has to be carried out first. This algorithm has the following steps: [12]

1. Set the induction factors, a and a', to be zero initially
2. Calculate the flow angle by use of formula 2.11
3. Calculate the local angle of attack by formula 2.12
4. Use the local angle of attack to find the lift coefficient and the drag coefficient, by curves or tabulated values
5. Use formula 2.17 and 2.18 to find the normal and tangential coefficients, which are a projection of the lift and drag coefficients
6. Calculate a and a' by formula 2.19 and 2.20
7. If the initial values given in step 1 do not match the values calculated in step 6, the algorithm must to be performed all over again. If instead the values are approximately the same, the blade element method is completed

The local loads can now be calculated, and by summing the contributions from each node, the loads on the blade root can be found. [12]

The projected coefficient normal to the rotor plane, C_n, due to drag and lift coefficient, is given by formula 2.17. [12]

$$C_n = C_l cos\phi + C_d sin\phi \tag{2.17}$$

The projected coefficient tangential to the rotor plane, C_t, due to drag and lift coefficient, is given by formula 2.18. [12]

$$C_t = C_l sin\phi - C_d cos\phi \tag{2.18}$$

The axial induction factor is given by formula 2.19. [12]

$$a = \frac{1}{\frac{4\,sin^2\,\phi}{\sigma C_n} + 1} \tag{2.19}$$

Here σ is the solidity, calculated by formula 2.21. [12]

The tangential induction factor is given by formula 2.20. [12]

$$a' = \frac{1}{\frac{4\,sin\,\phi\,cos\,\phi}{\sigma C_t} - 1} \tag{2.20}$$

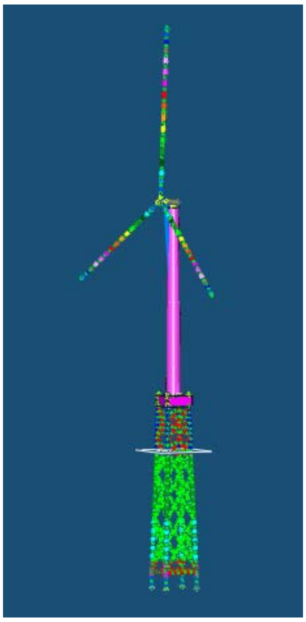
The solidity is calculated by formula 2.21. [12]

$$\sigma(r) = \frac{c(r)B}{2\pi r} \tag{2.21}$$

Here σ represents the fractional part of the annular area covered by blades. B denotes the number of blades. [12]

2.7 Fedem

Fedem is a multi-body software, where analysis takes place in a time-domain. The acronym Fedem stands for Finite Element Dynamics in Elastic Mechanisms. The software performs virtual testing of complex mechanical systems. This includes the capability to create, solve and post process data. Fedem is also equipped with solvers which provide fast and numerically stable results. It is possible to observe how the time domain analysis developed with time, through user interface. This means that it is possible to watch animations and curves under development. The Fedem software can be used for load analysis, stress analysis, eigenmode solutions, strain gage solutions and fatigue analysis. However, not all these aspects are fully functional in Fedem windpower, since the software is still under development. For instance fatigue analysis is not verified. [17]



Fedem windpower can be used as a tool to simulate how wind field causes aerodynamic loads on wind turbines. The wind field is generated by another software application. This can for instance be Turbsim, see Section 2.4. By use of the generated wind field, Fedem estimate among other things, loads at specific locations. [17]

Note: The model on the right side is created by Kristian Sætertrø, using Fedem software

2.8 Fatigue

Fatigue is a common source to failure in materials. It is a type of failure that occurs over a long period of time. Initially fatigue starts with a tiny crack, which grows non-linearly when subjected to repeating cyclic loads. However, non-linear growth is hard to measure, and to be able to estimate fatigue in a more convenient way, it can be assumed that cracks expands linearly. Palmer-Miner rule is used regarding this issue. See Sec. 2.8.3. [18]

To determine how much cyclic load of different load range, the blades on a wind turbine can withstand without collapsing, there has to be done some experimental tests. The results from these tests are sketched in curves called S-N curves. This is, in other words, the capacity to the material in the blades. [18] [19]

2.8.1 Rainflow counting method

The rainflow counting method, developed by the Japanese researchers Matsuishi and Endo, is needed when a material is exposed to irregular loads over a time period. It is needed in order to define fatigue based on Palmer-Miner rule. This rule requires closed cycles, and scaled cycles. The closed cycles are achieved by using the rainflow counting method, and the way to scale cycles are described in section 2.8.2. [18] [20]

The idea behind the rainflow counting method is to pair half-cycles that match each other, in both load mean and range. The half-cycles that match each other are equal in size (or rather equal), but directed in opposite direction. This is illustrated by arrows in Figure 2.9. When they are matched, they form a closed cycle. A closed cycle is illustrated in Figure 2.8. The half-cycles matched must not necessarily be neighbors, i.e. a half cycle at the start of a load history can be paired with a half-cycle at the end. [18] [20]

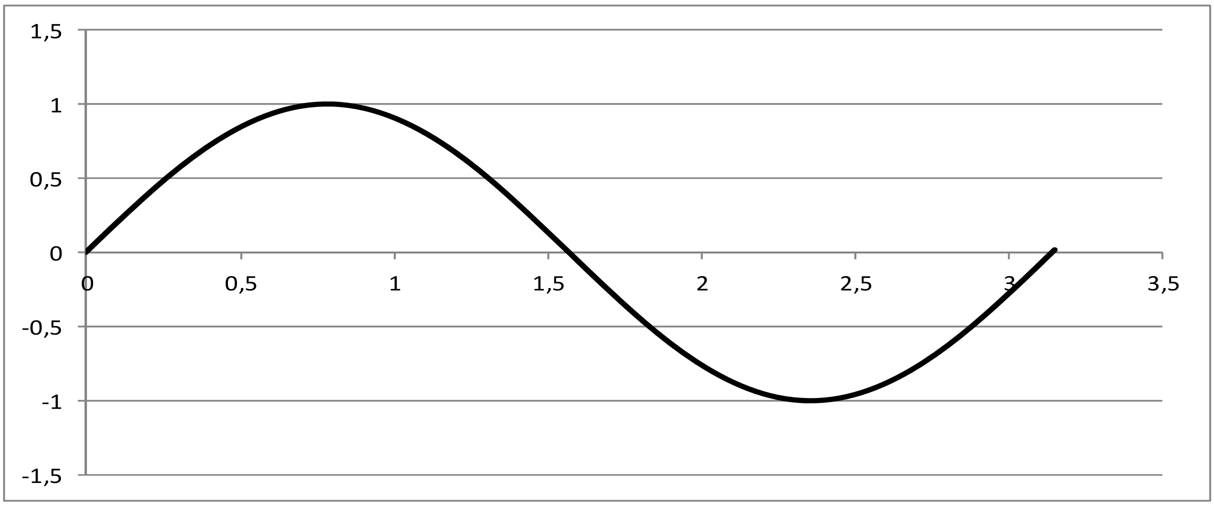


Figure 2.8 Closed cycle

The rainflow counting method may be illustrative described by use of Figure 2.9. First of all there has to be drawn straight lines from the valley to the peak and vice versa, throughout the load spectrum. Afterwards the load spectrum will be turned around 90 degrees clockwise. The result of this revolution is that positive x-axis is on right side, seen from the origin, and the negative x-axis on the opposite side. The sketch in Figure 2.9 has a zigzag pattern. This gave the Japanese researchers, Matsuishi and Endo, associations to a roof construction that exists in Japan, called pagoda roof. Their thoughts were to drop a raindrop on each "roof". These drop follows "the roof ", and fall to the ground when the following occurs: [20] [21]

- They pass a larger maximum. This occurs when the drop runs from right to left
- They pass a larger minimum. This occurs when the drop runs from left to right
- Hitting another drop when it flows down the "roof"
- Just fall out [21]

All the drops that fall to ground represent a half-cycle. Those who match each other are coupled. After performing rainflow counting one gets a matrix of closed cycles, where a cycle is defined by its own range and mean. [21]

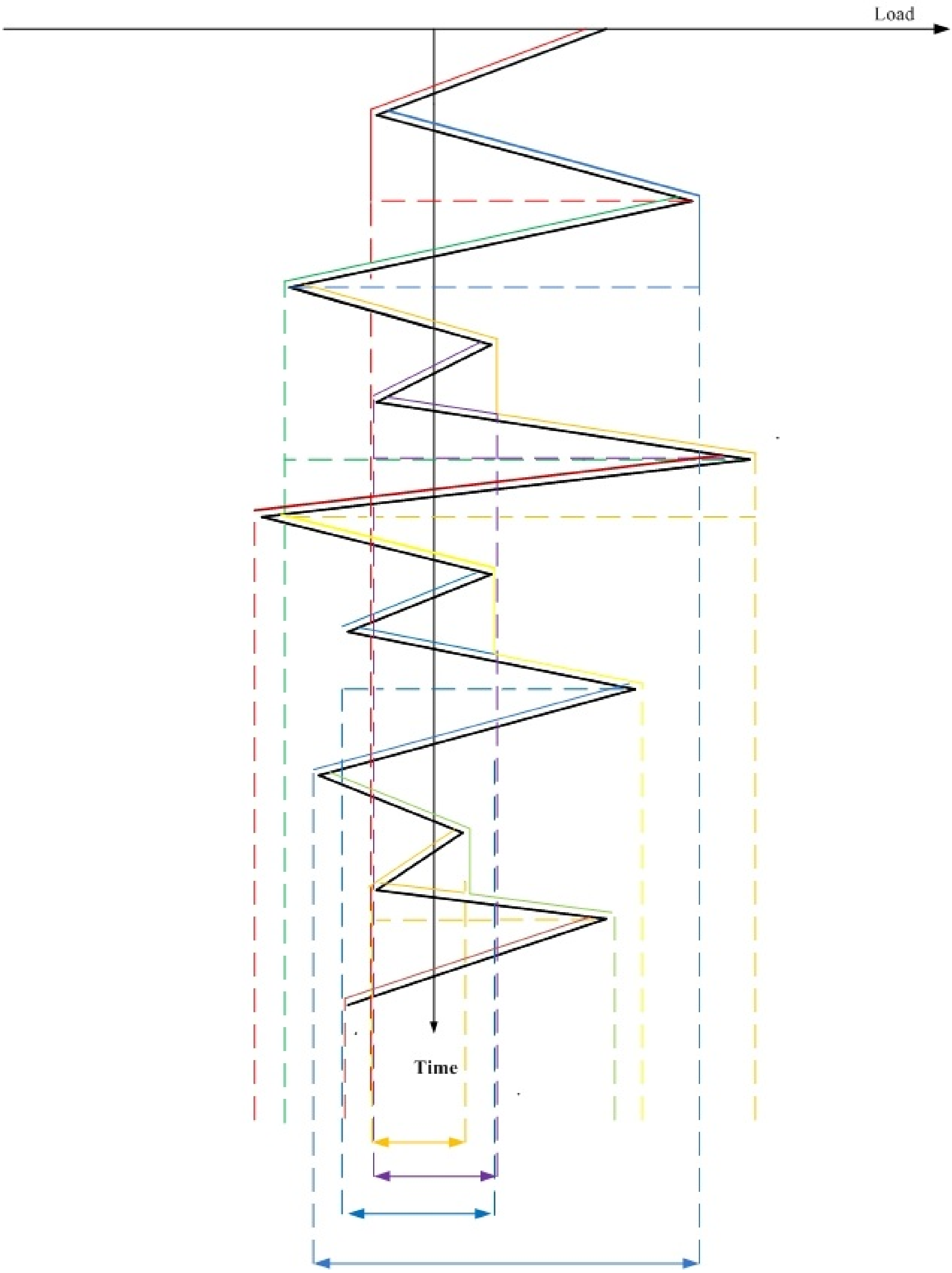


Figure 2.9 **Rainflow counting illustration** [21]

2.8.2 Scaling of cycles

Cycle scaling is necessary if there is a spectrum of mean loads, because the formulas used in the Miner's rule are based on cycle fluctuations around one mean load. The way to achieve one mean load, is to adjust each cycle's load range, by a factor equal or greater than 1, using the following formula: [19]

$$L_k^{RF} = L_k^R \left(\frac{(L^{ult}) - |L^{MF}|}{(L^{ult} - |L_k^M|)} \right) \qquad \textbf{2.22}$$

In formula 2.22, L_k^R, represents a load range of any cycle in the load spectrum. The corresponding mean load value is represented by, L_k^M. The abbreviation L^{MF} represents the fixed mean value, in which the cycles are scaled. L_{ult} is the ultimate design load of the material being examined. [19]

2.8.3 Miners Rule

The Miner's rule, developed by Palmgren and Miner, calculate fatigue in a structure due to cyclic loading. Each cycle contributes with its own fraction sum to the total damage. The contributions are added together, and failure occurs when these reaches unity. In the Miner rule it is assumed that a cycle of a certain size produces the same amount of damage, whether it is located in the beginning or end of the load history. The reality is that this cycle will cause less damage in the beginning than at the end. Despite this assumption, the rule is widely used. The Miner's rule is a simple rule, and can be written as follows: [18] [19]

$$D = \sum_k \frac{n_k}{N_k(L_k^{RF})} \qquad \textbf{2.23}$$

Here is the numerator, n_k , the number of cycles of a certain range. The denominator, $N_k(L_k^{RF})$, is a measured value for how many cycles that are required for the material to fail, given a certain load range of the cycle. In other words, N_k , is a function of L_k^{RF}, described in section 2.8.2. That means that each load range has its own number of cycles to failure. To be able to calculate this number, the following formula is used: [19]

$$N_k^F = \left(\frac{L^{ult} - |L^{MF}|}{0.5 L_k^{RF}} \right)^m \qquad \textbf{2.24}$$

In the formula, L^{ult}, means the ultimate design load for the component being analyzed. This is the maximum load that the component can be exposed to, including material factors. Further, the abbreviation inside the absolute value sign, L^{MF}, represents the fixed mean load. The exponent, m, is a number obtained by experimental testing. By using one can model an S-N curve. [19]

2.8.4 Damage Equivalent Load

The damage equivalent load for any load spectrum has a constant load range, fluctuates around a constant mean load, and has a constant frequency. It is a way to represent the same damage as the variable spectrum loads, calculated by Palmer- Miner rule. [19]

The damage equivalent load (DEL) is used to compare different kinds of load spectrum. To get an accurate basis for comparison, it is required that the frequency is set equal for the load spectra. In addition, the simulation time must have the same length. It also required that the S/N slopes, (m), have the same numerical values. When the three parameters mentioned above are set equal for different load spectrum, it is only DEL which varies due to different load spectra. Since only DEL changes, the comparison between the various load histories is easy. It is simply to conduct a relative comparison, i.e. how large the difference is in percent for different load spectra. [19]

The DEL is calculated using formula 2.29. To enable that, one needs formula 2.25 - 2.28. [19]

$$D_j^{ST} = \sum_k \frac{n_{jk}}{N_k} = \frac{n_j^{STeq}}{N_j^{eq}} \qquad \textbf{2.25}$$

In formula 2.25, D_j^{ST} represent the short-term damage for file j. Further, n_{jk} , means the count of a certain cycle in file j. N_k represent the number of cycles to failure at a given size of the cycle. n_j^{STeq} is the equivalent number of cycles, and N_j^{eq} is the equivalent number of cycles to failure. [19]

$$n_j^{STeq} = f^{eq} * T_j \qquad \textbf{2.26}$$

In formula 2.26, f^{eq} represent the chosen frequency, and T_j the elapsed time. [19]

$$N_j^{eq} = \left(\frac{L^{ult}}{\left(\frac{1}{2} DEL_j^{STF}\right)} \right)^m \qquad \textbf{2.27}$$

In formula 2.27, L^{ult} is the ultimate design load. The S/N-slopes is represented by m. [19]

$$L_k^{R0} = L_k^R \left(\frac{L^{ult}}{(L^{ult} - |L_k^M|)} \right) \qquad \textbf{2.28}$$

In formula 2.28 cycles are scaled about a zero mean. The abbreviation is explained below formula 2.22 [19]

$$DEL_j^{ST0} = \left(\frac{\sum_k (n_k (L_k^{R0})^m)}{n_j^{STeq}} \right)^{\frac{1}{m}} \qquad \textbf{2.29}$$

Formula 2.29 calculate the damage equivalent load. [19]

3 Methodology

The main goal for the thesis is to investigate the effect that seven different wind profiles have on the fatigue of the reference wind turbine. This chapter gives a step by step description of the methodology applied. At selected locations on the wind turbine fatigue analysis will be performed using the different wind profiles. These locations are blade root, tower top and tower bottom. In addition, a description of the wind turbine analyzed, will be given. To be able to perform the fatigue analysis the following software's have been used: Turbsim, Fedem, Mlife (Matlab application) and Microsoft Excel.

3.1 NREL offshore 5-MW baseline wind turbine

The 5-MW NREL wind turbine is used in the OC4-project. This is a wind turbine which originally was developed by the National Renewable Energy Laboratory in the United States (NREL). It is used as a mal for large, megawatt offshore wind turbines. Some properties for this wind turbine are listed in Table 3.1. [22]

Rating	5 MW
Rotor orientation, Configuration	Upwind, 3 blades
Rotor, Hub diameter	126 m, 3 m
Hub height	90.55 m
Cut-In, Rated, Cut-Out wind speed	3 m/s, 11.4 m/s, 25 m/s
Cut-In, Rated Rotor speed	6.9 rpm, 12.1 rpm
Rotor Mass	110 000 kg
Nacelle Mass	240 000 kg
Tower Mass	347 460 kg

Table 3.1 Properties for the NREL 5-MW Baseline Wind turbine [22]

3.2 Wind profiles

The names of the wind profiles used the analysis are given in Table 3.2:

Wind profiles	Abbreviations
Very unstable	VU
Unstable	U
Near unstable	NU
Neutral	NEU
Near stable	NS
Stable	S
Very stable	VS

Table 3.2 Names of the wind profiles

In the analysis there are two different formulas that describe the wind profiles; the logarithmic wind profile and the power law wind profile. The formulas are 2.3 and 2.7 respectively, given in the theory chapter.

The logarithmic wind profile for the analysis includes among other things, the Obukhov lengths given in Table 3.3.

Wind profiles	Monin-Obukhov lengths, L_{m0}, [m]
VU	-74
U	-142
NU	-314
NEU	5336
NS	318
S	104
VS	28

Table 3.3 Monin-Obukhov lengths for the seven wind profiles

Note: The obukhov lengths are given by supervisor Lene Eliassen

It is these lengths that cause different stability correction parameters, which in turn provides seven different logarithmic wind profiles.

In addition to the stability correction parameter, three other parameters are needed in order to obtain the logarithmic wind profile. One of them is the reference height, H. The reference height for the reference wind turbine is 90.55 m above still sea water level, which is the hub height. The corresponding wind speed is the reference speed, U (H), chosen to be 11.4 m/s. This wind speed represents the mean wind speed at hub height.

The last parameter needed is the roughness length z_0, which is calculated by formula 2.2. In the analysis the z_0-value is chosen to be 0.001. In order to obtain that the A_c constant is given the value 0.0615. An overview of the parameters used to calculate the roughness length is given in Table 3.4.

Parameter names	Abbreviations	Values	Entities
Charnock's constant	A_c	0.0615	[-]
Karman's constant	κ_a	0.4	[-]
Gravity	g	9.81	[m/s^2]
Reference wind speed	U(H)	11.4	[m/s]
Reference height	H	90.55	[m]
Roughness length (calculated)	$\mathbf{z_0}$	**0.001**	**[m]**

Table 3.4 Roughness length

By using the information given so far, it is possible to calculate the seven logarithmic wind profiles. The calculated values are tabulated in Table 8.2 and Table 8.3 in Appendix.

However in this analysis, power law wind profiles are used instead. This is done because of limitation in the analysis application Turbsim, which is used to generate wind fields. The limitation implies that Turbsim only makes it possible to analyze the neutral atmosphere, in which stability is not taken into account. However the analysis requires that the stability correction parameters, ψ, are taken into account, because these create the seven wind profiles.

Therefore a method called curve fitting is used, in which the power law wind profile is adjusted until it fits the corresponding logarithmic wind profile, such that the stability correction parameter is included in the analysis. This implies to use formula 2.3 and 2.7, in which the α-exponent represent the adjustment. The adjustment is done by Excel spread sheet, and it is used a log-log scale to better see the best fit. Illustration of curve fitting is given in Figure 3.1, as well as Figure 8.1- Figure 8.7 in Appendix.

As can be seen in the figures, not all adjustments are equally accurate. This appears particularly in Figure 8.7, and also to some extent in Figure 8.6. For this reason the expected results for these two power law wind profiles, will not match the corresponding logarithmic wind profiles, which is the basis for the seven wind profiles analyzed. Due to this, inaccuracies will occur.

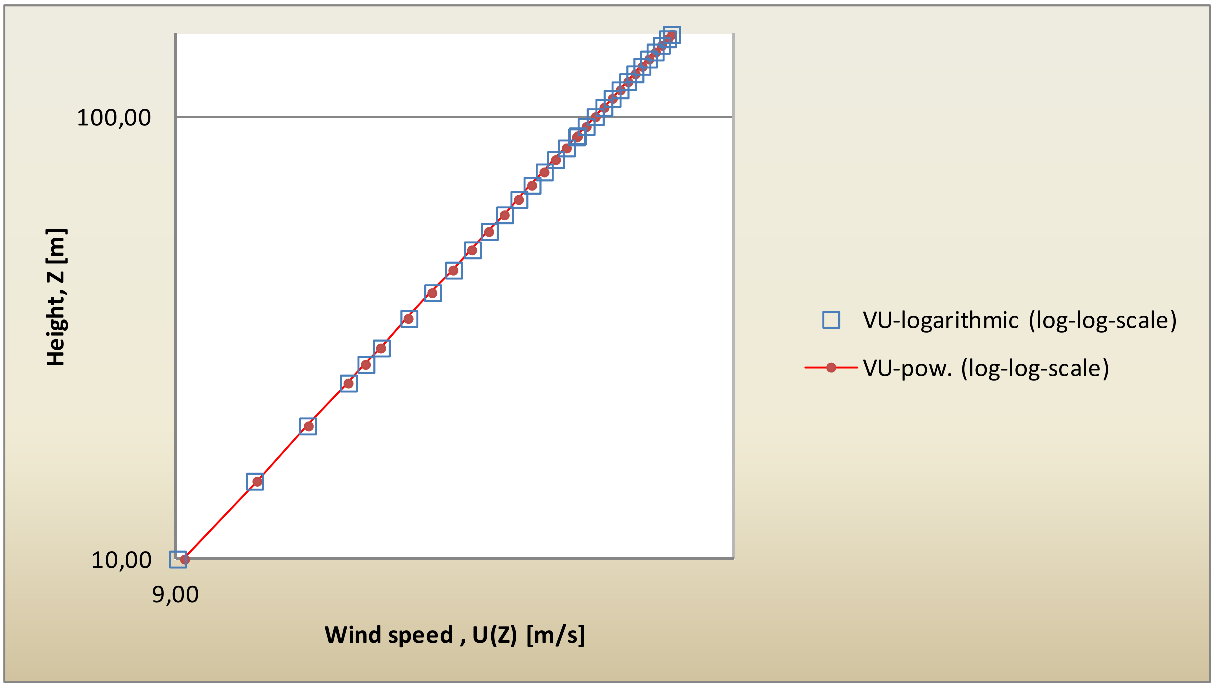


Figure 3.1 Curve fitting of VU-logarithmic vs. VU-power law

Curve fitting is done for all seven wind profiles, and the alpha parameters obtained are tabulated in Table 3.5 below.

Wind profiles	α - parameters
VU	0.105
U	0.102
NU	0.100
NEU	0.093
NS	0.086
S	0.082
VS	0.059

Table 3.5 α – parameters

Now it is possible to calculate and illustrate the seven power law wind profiles, which is used in the analyses. They are illustrated in Figure 3.2 below, and calculated in Table 8.4 in Appendix.

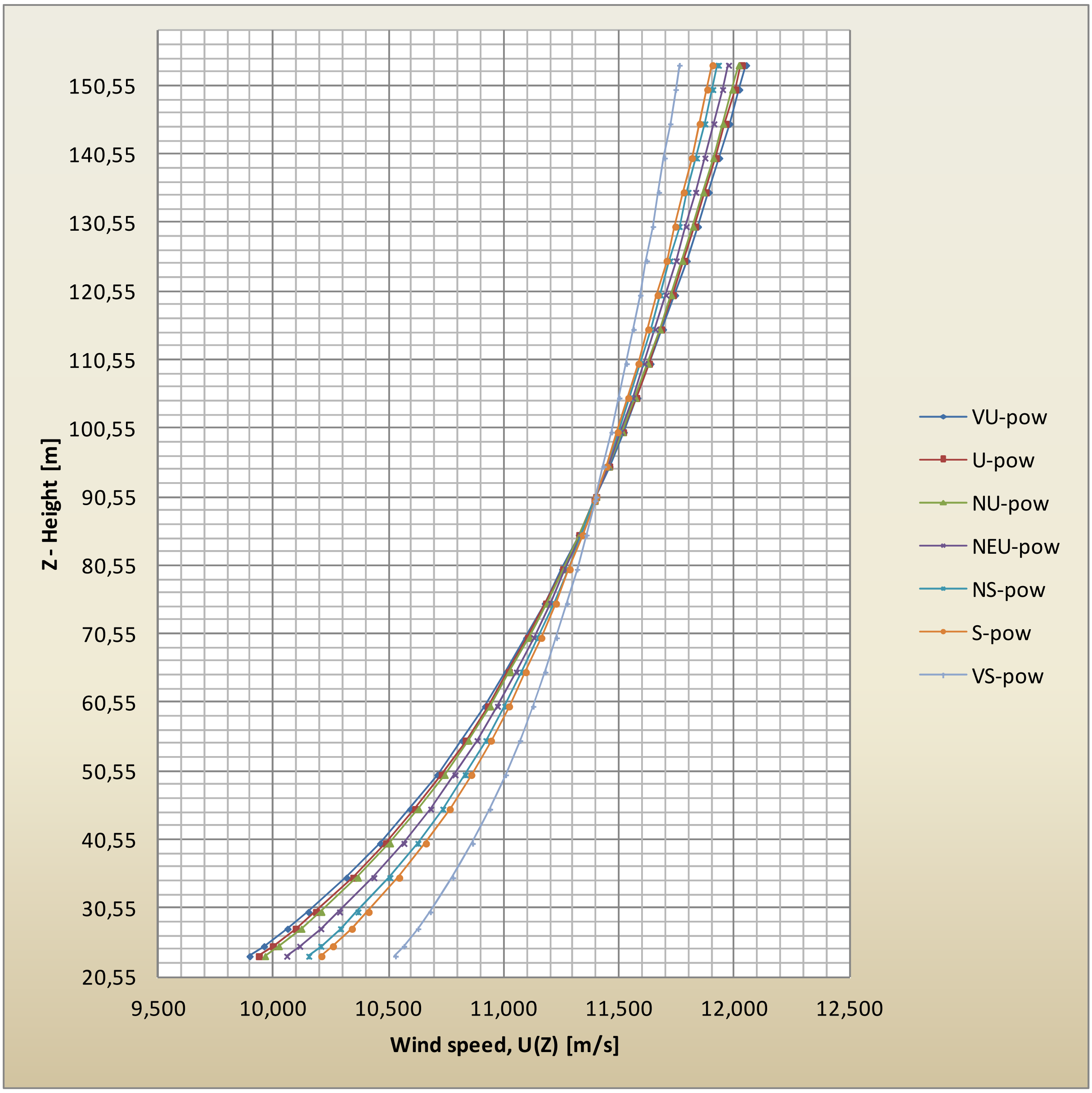


Figure 3.2 **The seven power law wind profiles**

In Figure 3.2 above the seven different power law wind profiles, define by the α-parameters, are collected. The height on the z-axis, from the bottom value of 23.55 m to the top value of 153.55 m, creates aerodynamic loads which in turn causes fatigue damage on the wind turbine blades. This propagates then to the tower top and bottom.

It can be seen from Figure 3.2 that the seven wind profiles only differs slightly from each other. Due to this, it is not expected such a large difference in fatigue damage at the blade root, for the seven wind profiles. But still there is a difference, and one way to determine the wind profile that has the greatest impact on the wind turbine, is to calculate the areas for the wind profiles in the height interval 23.55 m – 153.55 m. This is done by integration of the formulas tabulated in Table 3.6. The formulas are found by the trend line function in Excel.

Wind profiles	Formulas integrated in the interval z = 23.55m-153.55m	Integrated values (areas)	Normalized with respect to NEU
VU	1.16ln(z) +6.17	1463.6	0.9987 (0.13%)
U	1.13ln(z)+6.31	1464.0	0.9990 (0.10%)
NU	1.11ln(z)+6.41	1464.4	0.9993 (0.07%)
NEU	1.03ln(z)+6.75	1465.4	1.000
NS	0.98ln(z)+6.99	1466.3	1.0006 (0.05%)
S	0.91ln(z)+7.29	1467.3	1.0012 (0.12%)
VS	0.66ln(z)+8.42	1471.1	1.0039 (0.39%)

Table 3.6 Integrated values of the wind profiles

3.3 Turbulence

In this analysis there have been used three values for the turbulence intensity. The first one has been chosen and set to 25 %. The second has been calculated by use of formula 2.8. In order to do so one has to calculate the standard deviation, which is given by formula 2.9. The result of this calculation gives a turbulence intensity of 11 %. The third value has been set to 0 %.

By reducing the turbulence intensity from 25 % to 11 % to 0%, it is possible to analyze the effects that this has on fatigue.

3.4 Wind field and grid

In the methodology chapter so far, the wind profiles and three cases of turbulence have been determined. By combining a wind profile with one of the turbulence intensities, the result is a wind field. An illustration of a wind field is given in Figure 2.1.

In the analyses the grid height and width are set equal to 130 meter. This covers an area of the rotor diameter, plus a little extra (4 m below the rotor and 2 m on each side). The rotor diameter for the reference wind turbine is 126 meter.

3.5 Turbsim

In order to analyze how the seven power law wind profile differs in terms of wind speed, it is necessary to generate wind fields. This is done by use of the software application called Turbsim. A total of 91 wind fields are generated.

First of all, the seven wind profiles are generated with a turbulence intensity of 25 %. For each of these wind profiles there have been carried out six runs (recommended by IEC), where the runs are separated by its seed number. This is done to take care of the randomness due to simulation of turbulence. By doing six simulations large deviations from the mean results will be discovered and the confidence in the comparison of the wind profiles is improved. I.e. if one run has a large deviation from the mean speed due to turbulence, this run will not be representative when comparing to other wind profiles. Later on in this document the damage equivalent load (DEL) will be calculated, and the six runs done by Turbsim will then cause six DEL. Of these, there will be calculated an average DEL.

The procedure in the previous section has been repeated for the turbulence intensity of 11%. For the turbulence intensity of 0 %, there has only been performed one run for each wind profile, as deviation from mean values are not an issue for 0 % turbulence.

A text file from Turbsim is also presented in appendix on page 66.

3.6 Fedem

In order to perform analyses of the loads that affect the wind turbine, the multi-body software called Fedem can be used. The software uses the wind fields generated by Turbsim. A description of how this software is given in the theory chapter, see Section 2.7.

In the analysis carried out for this thesis, results have been exported from Fedem for three specific locations. The specific locations are at blade root, tower top and tower bottom. For each of these locations the total load picture is given by six loads; forces in x, y and z-direction and bending moment in x, y and z direction. The loads extracted from Fedem simulations are given in Table 3.7. They are exported from Fedem together with the corresponding wind speed in x, y, and z-direction, as well as time. The time is divided into time steps at an interval of 0.05 second. At this time steps information are calculated and stored. For each simulation performed, the total simulation time is 650 seconds. The fifty first of these is neglected due to extremely high vibration at the start of the simulation. The reason that the effect is so large at first is that the wind turbine experiences an airflow that changes from 0 m/s to an air flow of 10-12 m/s, in a fraction of a second. This never happens in real life. What then remains of the simulation is 600 seconds/10 minutes. This is the recommended time for this type of simulations according to IEC 61400-3. [23]

Loads	Abbreviation
Force in x-direction at blade root	RFx
Force in y-direction at blade root	RFy
Force in z-direction at blade root	RFz
Bending moment in x-direction at blade root	RMx
Bending moment in y-direction at blade root	RMy
Bending moment in z-direction at blade root	RMz
Force in x-direction at tower top	TTFx
Force in y-direction at tower top	TTFy
Force in z-direction at tower top	TTFz
Bending moment in x-direction at tower top	TTMx
Bending moment in y-direction at tower top	TTMy
Bending moment in z-direction at tower top	TTMz
Force in x-direction at tower bottom	TBFx
Force in y-direction at tower bottom	TBFy
Force in z-direction at tower bottom	TBFz
Bending moment in x-direction at tower bottom	TBMx
Bending moment in y-direction at tower bottom	TBMy
Bending moment in z-direction at tower bottom	TBMz

Table 3.7 Loads extracted from the Fedem simulations

The loads extracted from the Fedem simulations are tabulated in Table 3.7, and the coordinate axes are defined in Figure 2.3.

3.7 Rainflow counting

The fatigue distribution which affect the wind turbine, create an arbitrarily and complex load spectrum over time. To be used in fatigue computation something has to be done with this complex spectrum. The first method to be used in order to reduce the complexity is the rainflow counting method. The method is described in section 2.8.1. A typical load fluctuation, if turbulence is present, may look like the snap shot given in Figure 3.3. [20]

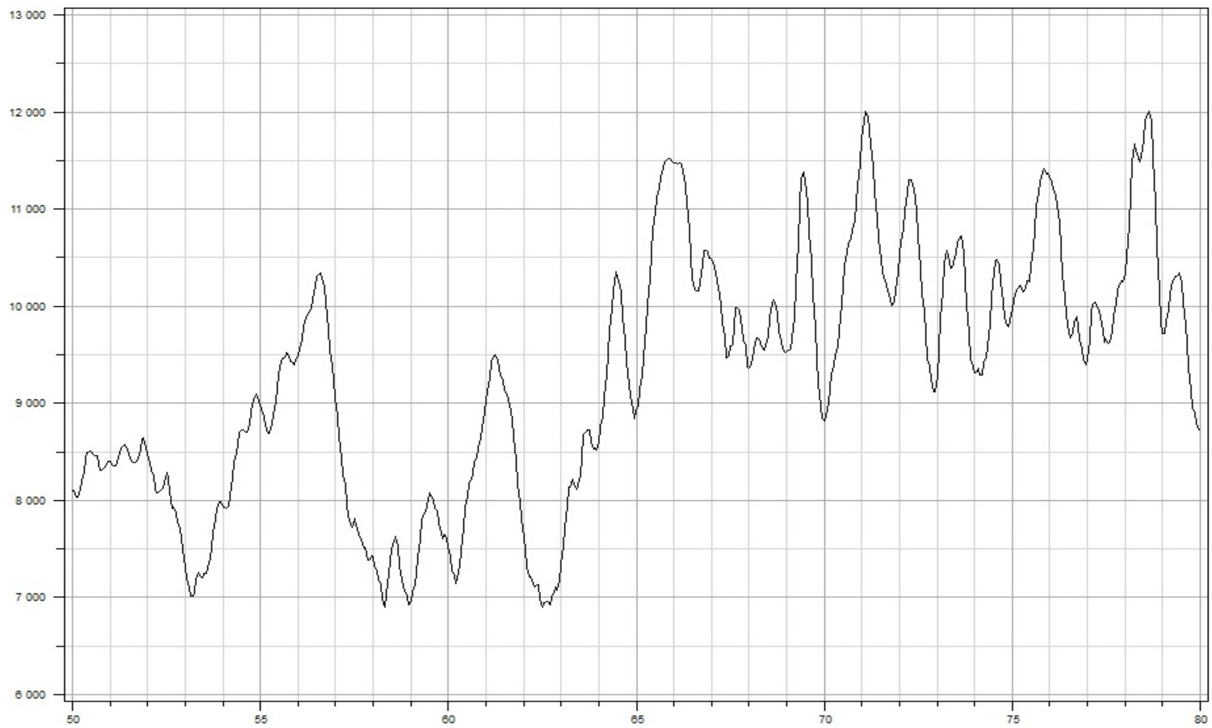


Figure 3.3 **Typical load fluctuation** (extracted from Fedem)

After the rainflow counting is completed, the cycles will be scaled. The description and formula is given in section 2.8.2. In this analysis, the cycles are scaled about zero mean.

3.8 Binning the load range

So far in the preparation of the load situation, the cycles are closed and collected at zero mean. This is illustrated in Figure 3.4. This figure also illustrates how the load ranges are binned. By using the first cycle with a range of 130 in the following discussion, one can see the importance of binning the load range. If only three bins are used this range will end up in bin 120-180. Then this cycle will get a range value of 150, i.e. (180-120) / 2 = 150. If the number of bins is doubled, it will end up in bin 120-150 and get a value of 135. By doubling the number of bins once again the same cycle will end up in the bin 120-135 and get a value of 127.5. The last range is closest to the actual range of 130. This shows that the load range converges alternating towards a certain value. Therefore, in order to achieve a good precision in the result, the number of bins is relevant.

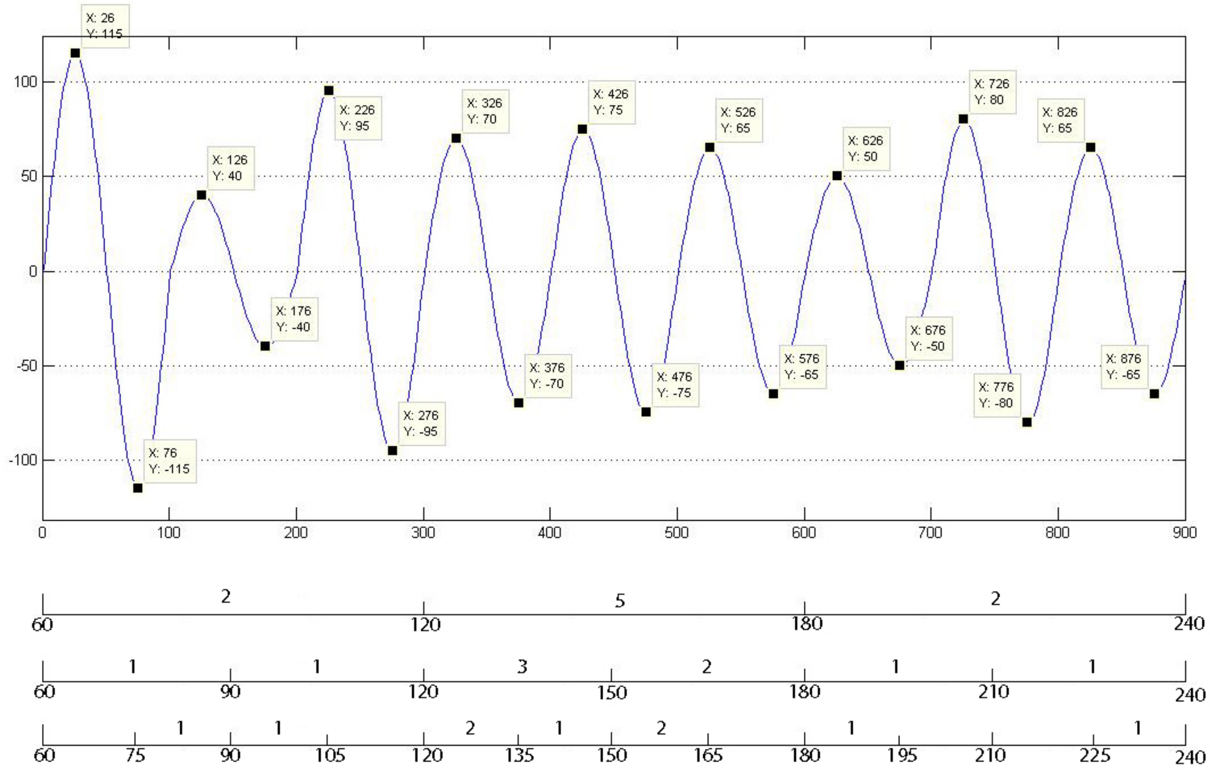


Figure 3.4 Binning the load range [1]

In the analysis the number of bins is chosen to be 50, for the run with smallest load range. The reason why 50 bins are used can be explained by the numbers tabulated in Table 3.8. Table 3.8 shows alternating convergence towards certain values, and 50 bins are reasonably accurate.

RMy															
Bins	1	2	5	10	20	35	40	45	48	50	52	64	75	76	84
	Damage equivalent load (DEL)														
VU	709	948	945	999	1020	1020	1020	1020	1020	1020	1020	1020	1020	1020	1020
U	723	965	972	1020	1040	1030	1040	1040	1040	1030	1030	1040	1040	1040	1040
NU	735	976	990	1030	1050	1040	1050	1050	1040	1050	1040	1050	1040	1040	1040
NEU	759	984	1010	1050	1070	1070	1070	1060	1060	1070	1060	1060	1070	1070	1060
NS	765	965	994	1050	1070	1070	1070	1070	1070	1070	1070	1070	1070	1070	1070
S	775	959	1000	1060	1070	1070	1070	1070	1060	1070	1070	1070	1070	1070	1070
VS	792	859	1030	1090	1090	1090	1080	1080	1080	1090	1090	1090	1080	1080	1090
	Normalized with respect to the neutral wind profile														
VU (%)	0,934	0,963	0,936	0,951	0,953	0,953	0,953	0,962	0,962	0,953	0,962	0,962	0,953	0,953	0,962
U (%)	0,953	0,981	0,962	0,971	0,972	0,963	0,972	0,981	0,981	0,963	0,972	0,981	0,972	0,972	0,981
NU (%)	0,968	0,992	0,980	0,981	0,981	0,972	0,981	0,991	0,981	0,981	0,981	0,991	0,972	0,972	0,981
NEU (%)	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
NS (%)	1,008	0,981	0,984	1,000	1,000	1,000	1,000	1,009	1,009	1,000	1,009	1,009	1,000	1,000	1,009
S (%)	1,021	0,975	0,990	1,010	1,000	1,000	1,000	1,009	1,000	1,000	1,009	1,009	1,000	1,000	1,009
VS (%)	1,043	0,873	1,020	1,038	1,019	1,019	1,009	1,019	1,019	1,019	1,028	1,028	1,009	1,009	1,028

Table 3.8 Changes in DEL for RMy due to varying number of bins

Note: In Table 3.8 DEL is calculated for the RMy. The numbers are based on the smallest load range for turbulence intensity of 0 %.

[1] The illustration is a collaboration between O.M. Stava and G-M. S. Gudmundsen

Because Table 3.8 shows that 50 bins are sufficient, the smallest load range is divided by 50 for all load cases. This gives the bin widths tabulated in Table 3.9, and is used for each run.

Loads	Bin width	Loads	Bin width
RFx	0.7	TTMx	2.6
RFy	7.1	TTMy	16.9
RFz	7.0	TTMz	10.5
RMx	145.5	TBFx	1.6
RMy	32.8	TBFy	0.3
RMz	2.4	TBFz	0.3
TTFx	1.6	TBMx	18.8
TTFy	0.2	TBMy	104.7
TTFz	0.3	TBMz	10.7

Table 3.9 Bin widths found by dividing the smallest load range of the 91 runs by 50

3.9 Calculation of damage equivalent load

To be able to calculate damage equivalent load (DEL), a MatLab application called Mlife is used. A text file is presented in Appendix on page 68. With this application rainflow counting, cycle scaling and binning of the load range are calculated. In addition, the ultimate load needs to be defined. The ultimate load is not an important parameter in the analyses performed, but it is important that it is much larger than the max load in each run. The parameter m in Mlife represents the inverse slope of an S/N curve. This parameter differs from material to material. In the analyses m is chosen to be 12 for the blade root and 5 for the tower, same as values used in reference [24].

The important parameters needed are now defined, and by using Mlife the DEL's can be calculated for each load case. The results are tabulated and illustrated in the next chapter.

4 Results

In this chapter the results for fatigue is presented. I.e. the relative fatigue calculated by damage equivalent load (DEL). The tables below show DEL for seven wind profiles, where 18 load cases are presented for each wind profile. In addition, three turbulence intensities for each wind profile are presented. In Table 4.2, Table 4.4 and Table 4.6, the DEL's are normalized with respect to the neutral wind profile.

For turbulence intensity (TI) of 25 % and 11 % six runs are conducted for each wind profile, and the mean value for each of the six runs are calculated. For TI of 0 % only one run has been performed for eacg wind profile. These results are given in Table Table 8.5 -Table 8.18 in the Appendix.

Some selected graphical presentations of the results are given in this chapter. The remaining results are illustrated in the Appendix.

Run	RFx	RFy	RFz	RMx	RMy	RMz	TTFx	TTFy	TTFz	TTMx	TTMy	TTMz	TBFx	TBFy	TBFz	TBMX	TBMY	TBMZ
VU	178	271	347	5947	6857	213	199	58	51	714	3222	3507	204	66	54	4418	13817	3543
U	186	270	364	5910	7247	210	196	57	50	715	3223	3408	205	64	53	4285	13883	3445
NU	183	273	336	6002	7097	232	200	73	50	718	3167	3468	204	86	54	5650	14183	3505
NEU	185	272	348	5952	7067	183	199	64	50	705	3188	3410	203	74	53	4888	14050	3448
NS	183	271	363	5983	7025	211	198	73	49	738	3230	3380	204	85	52	5648	13883	3418
S	182	273	354	5985	7008	201	196	62	50	714	3178	3482	198	72	54	4790	13833	3518
VS	189	270	360	5918	7135	184	197	69	49	718	3188	3368	205	80	53	5307	13950	3407

Table 4.1 DEL due to 25 % TI

Run	RFx	RFy	RFz	RMx	RMy	RMz	TTFx	TTFy	TTFz	TTMx	TTMy	TTMz	TBFx	TBFy	TBFz	TBMX	TBMY	TBMZ
VU	0,964	0,998	0,999	0,999	0,970	1,164	0,996	0,917	1,017	1,013	1,010	1,028	1,003	0,895	1,015	0,904	0,983	1,028
U	1,006	0,993	1,048	0,993	1,025	1,146	0,981	0,895	0,991	1,014	1,011	1,000	1,008	0,871	0,991	0,877	0,988	0,999
NU	0,991	1,005	0,967	1,008	1,004	1,265	1,003	1,148	1,007	1,019	0,993	1,017	1,007	1,161	1,004	1,156	1,009	1,016
NEU	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
NS	0,992	0,999	1,043	1,005	0,994	1,152	0,994	1,152	0,978	1,046	1,013	0,991	1,005	1,153	0,976	1,155	0,988	0,991
S	0,987	1,004	1,017	1,006	0,992	1,097	0,981	0,978	1,009	1,012	0,997	1,021	0,977	0,981	1,006	0,980	0,985	1,020
VS	1,025	0,995	1,036	0,994	1,010	1,004	0,989	1,088	0,985	1,018	1,000	0,988	1,010	1,082	0,985	1,086	0,993	0,988

Table 4.2 DEL normalized with respect to the neutral wind profile for 25 % TI

Run	RFx	RFy	RFz	RMx	RMy	RMz	TTFx	TTFy	TTFz	TTMx	TTMy	TTMz	TBFx	TBFy	TBFz	TBMX	TBMY	TBMZ
VU	100	262	284	5512	4007	122	115	36	26	402	1605	1678	117	42	28	2787	8178	1693
U	107	261	288	5478	4410	120	120	31	25	388	1563	1615	120	36	27	2388	8488	1635
NU	105	261	280	5485	4198	124	121	36	26	399	1505	1630	122	43	28	2832	8735	1650
NEU	108	262	284	5508	4310	139	120	34	25	398	1562	1607	121	40	27	2665	8605	1622
NS	106	261	280	5488	4217	135	117	36	25	407	1610	1615	118	42	27	2773	8372	1633
S	105	261	282	5505	4187	119	118	32	26	392	1547	1632	118	37	27	2435	8383	1650
VS	104	261	281	5468	4047	132	117	35	25	403	1558	1587	118	41	27	2755	8320	1607

Table 4.3 DEL due to 11 % (TI)

Run	RFx	RFy	RFz	RMx	RMy	RMz	TTFx	TTFy	TTFz	TTMx	TTMy	TTMz	TBFx	TBFy	TBFz	TBMX	TBMY	TBMZ
VU	0,923	1,000	1,001	1,001	0,930	0,879	0,965	1,043	1,037	1,010	1,028	1,045	0,964	1,044	1,031	1,046	0,950	1,044
U	0,986	0,997	1,014	0,995	1,023	0,865	1,001	0,907	0,997	0,975	1,001	1,005	0,993	0,893	0,996	0,896	0,986	1,008
NU	0,967	0,999	0,988	0,996	0,974	0,890	1,015	1,055	1,016	1,003	0,964	1,015	1,008	1,063	1,013	1,063	1,015	1,017
NEU	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
NS	0,978	0,998	0,988	0,996	0,978	0,974	0,978	1,044	0,999	1,022	1,031	1,005	0,975	1,035	0,998	1,041	0,973	1,007
S	0,968	0,999	0,992	0,999	0,971	0,853	0,986	0,918	1,003	0,985	0,990	1,016	0,971	0,912	0,999	0,914	0,974	1,017
VS	0,957	0,997	0,989	0,993	0,939	0,951	0,979	1,032	0,973	1,012	0,998	0,988	0,977	1,029	0,973	1,034	0,967	0,991

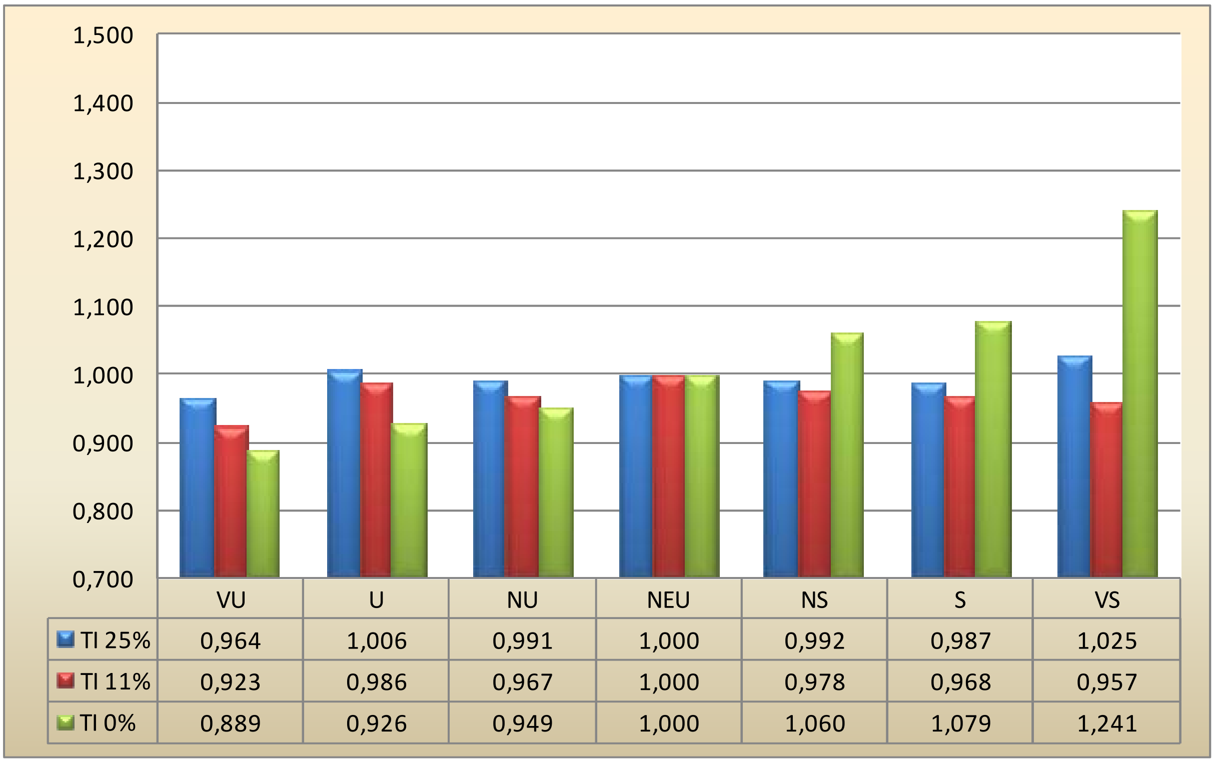
Table 4.4 DEL normalized with respect to the neutral wind profile for 11 % TI

Run	RFx	RFy	RFz	RMx	RMy	RMz	TTFx	TTFy	TTFz	TTMx	TTMy	TTMz	TBFx	TBFy	TBFz	TBMX	TBMY	TBMZ
VU	19	255	265	5310	1020	81	23	3	6	53	385	289	23	5	6	284	1600	292
U	20	255	265	5310	1040	81	25	3	6	53	381	286	25	5	6	276	1740	289
NU	21	255	265	5310	1040	81	25	4	6	54	379	283	25	5	6	288	1760	287
NEU	22	255	265	5310	1070	82	28	3	6	54	370	274	28	4	6	255	1970	278
NS	23	255	265	5310	1070	82	30	3	6	55	363	266	30	5	7	271	2170	269
S	23	255	265	5310	1070	82	32	4	6	55	360	261	32	5	7	300	2270	265
VS	27	255	263	5310	1090	83	39	4	6	59	338	242	39	5	7	308	2820	246

Table 4.5 DEL due to 0 % TI

Run	RFx	RFy	RFz	RMx	RMy	RMz	TTFx	TTFy	TTFz	TTMx	TTMy	TTMz	TBFx	TBFy	TBFz	TBMX	TBMY	TBMZ
VU	0,889	1,000	1,000	1,000	0,953	0,998	0,841	1,111	0,986	0,980	1,041	1,055	0,835	1,109	0,977	1,114	0,812	1,050
U	0,926	1,000	1,000	1,000	0,972	0,998	0,895	1,088	0,984	0,985	1,030	1,044	0,899	1,085	0,975	1,082	0,883	1,040
NU	0,949	1,000	1,000	1,000	0,972	0,999	0,910	1,144	0,990	0,993	1,024	1,033	0,903	1,111	0,983	1,129	0,893	1,032
NEU	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
NS	1,060	1,000	1,000	1,000	1,000	1,001	1,097	1,072	1,010	1,015	0,981	0,971	1,083	1,053	1,012	1,063	1,102	0,968
S	1,079	1,000	1,000	1,000	1,000	1,001	1,144	1,203	1,026	1,026	0,973	0,953	1,137	1,141	1,032	1,176	1,152	0,953
VS	1,241	1,000	0,992	1,000	1,019	1,021	1,412	1,239	1,054	1,100	0,914	0,883	1,399	1,185	1,069	1,208	1,431	0,885

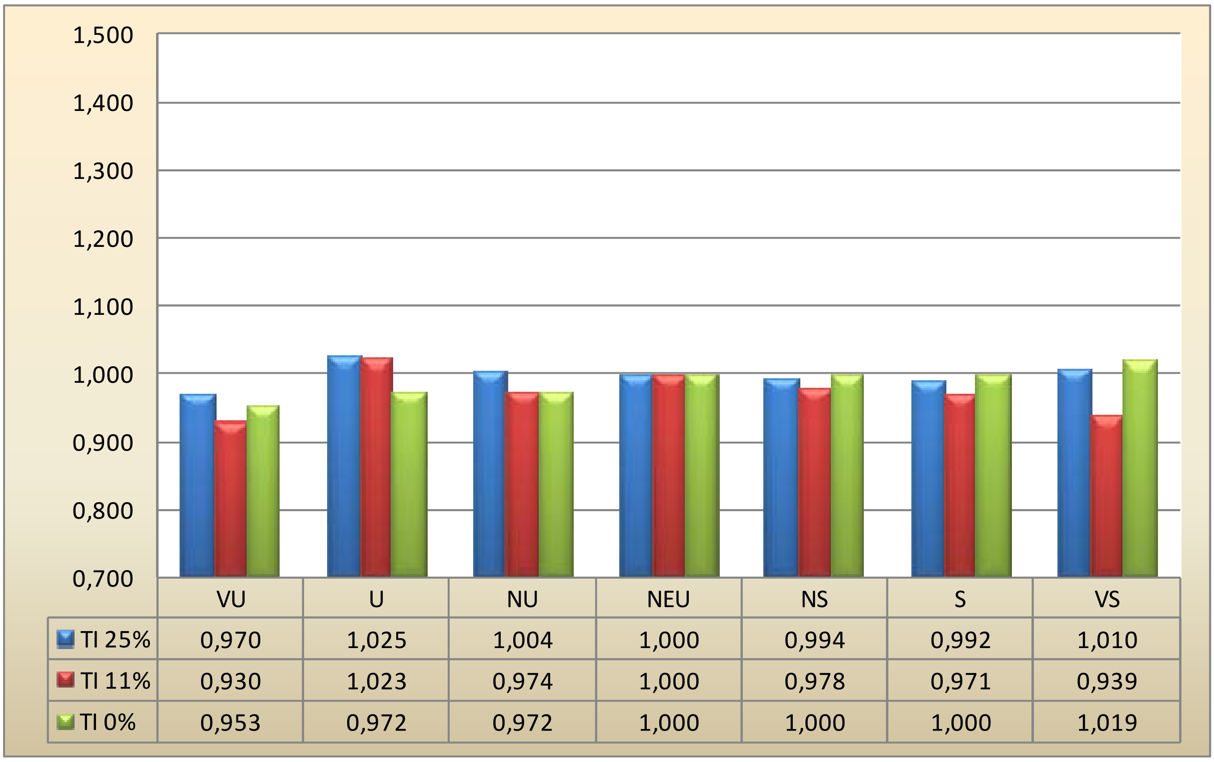
Table 4.6 DEL normalized with respect to the neutral wind profile for 0 % TI



	VU	U	NU	NEU	NS	S	VS
TI 25%	0,964	1,006	0,991	1,000	0,992	0,987	1,025
TI 11%	0,923	0,986	0,967	1,000	0,978	0,968	0,957
TI 0%	0,889	0,926	0,949	1,000	1,060	1,079	1,241

Figure 4.1 RFx – DEL due to force in x-direction at blade root.

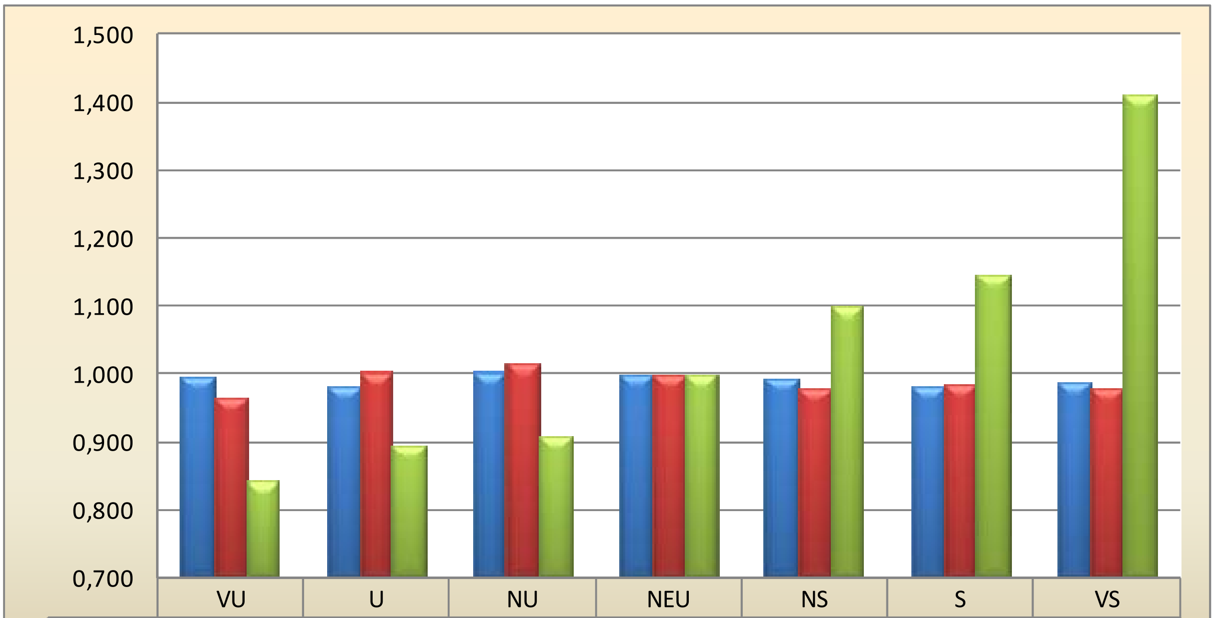
Note: Seven wind profiles and three different turbulence intensities are illustrated. DEL is normalized with the neutral wind profile.



	VU	U	NU	NEU	NS	S	VS
TI 25%	0,970	1,025	1,004	1,000	0,994	0,992	1,010
TI 11%	0,930	1,023	0,974	1,000	0,978	0,971	0,939
TI 0%	0,953	0,972	0,972	1,000	1,000	1,000	1,019

Figure 4.2 RMy - DEL due to bending moment in y-direction at blade root.

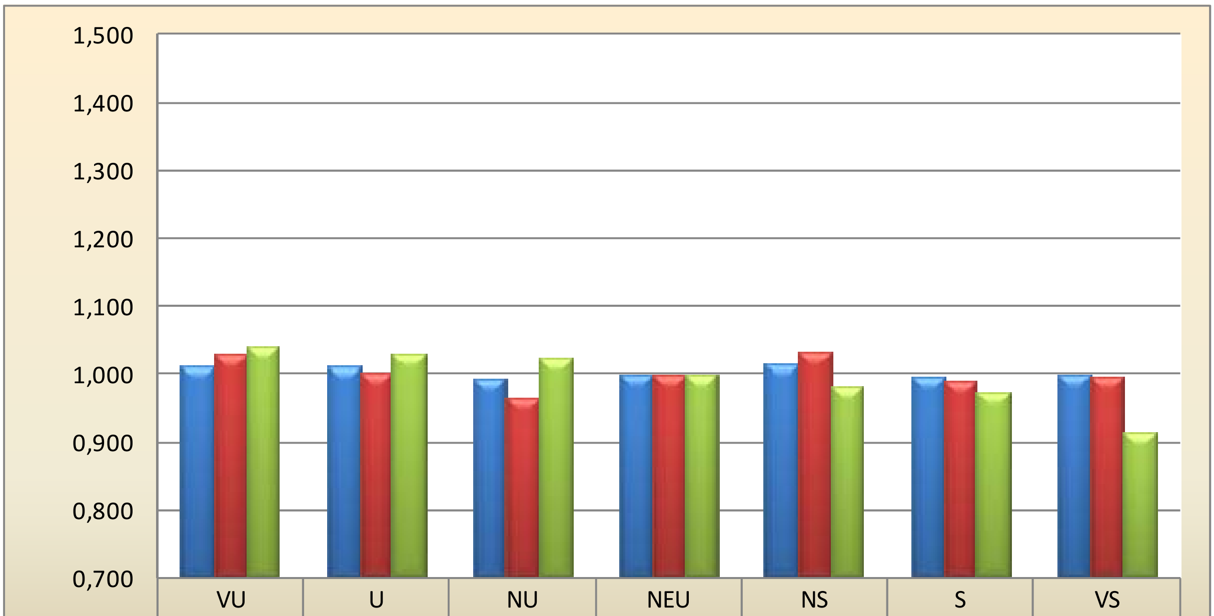
Note: Seven wind profiles and three different turbulence intensities are illustrated. DEL is normalized with the neutral wind profile.



	VU	U	NU	NEU	NS	S	VS
TI 25%	0,996	0,981	1,003	1,000	0,994	0,981	0,989
TI 11%	0,965	1,001	1,015	1,000	0,978	0,986	0,979
TI 0%	0,841	0,895	0,910	1,000	1,097	1,144	1,412

Figure 4.3 TTFx - DEL due to force in x-direction at tower top.

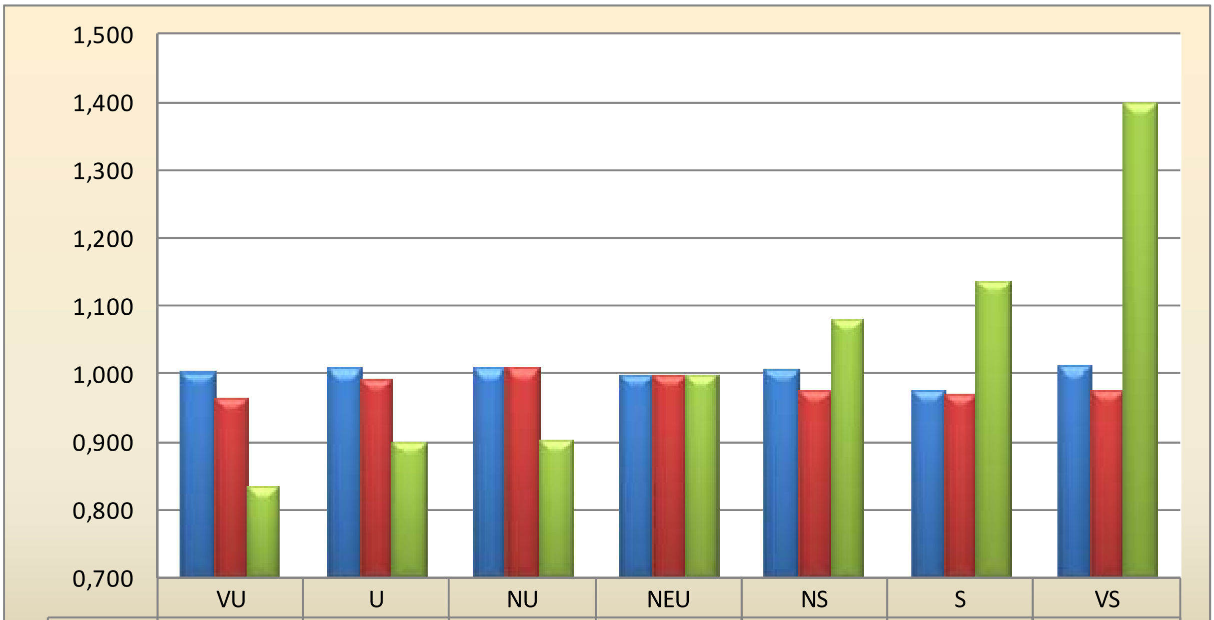
Note: Seven wind profiles and three different turbulence intensities are illustrated. DEL is normalized with the neutral wind profile.



	VU	U	NU	NEU	NS	S	VS
TI 25%	1,010	1,011	0,993	1,000	1,013	0,997	1,000
TI 11%	1,028	1,001	0,964	1,000	1,031	0,990	0,998
TI 0%	1,041	1,030	1,024	1,000	0,981	0,973	0,914

Figure 4.4 TTMy - DEL due to bending moment in y-direction at tower top.

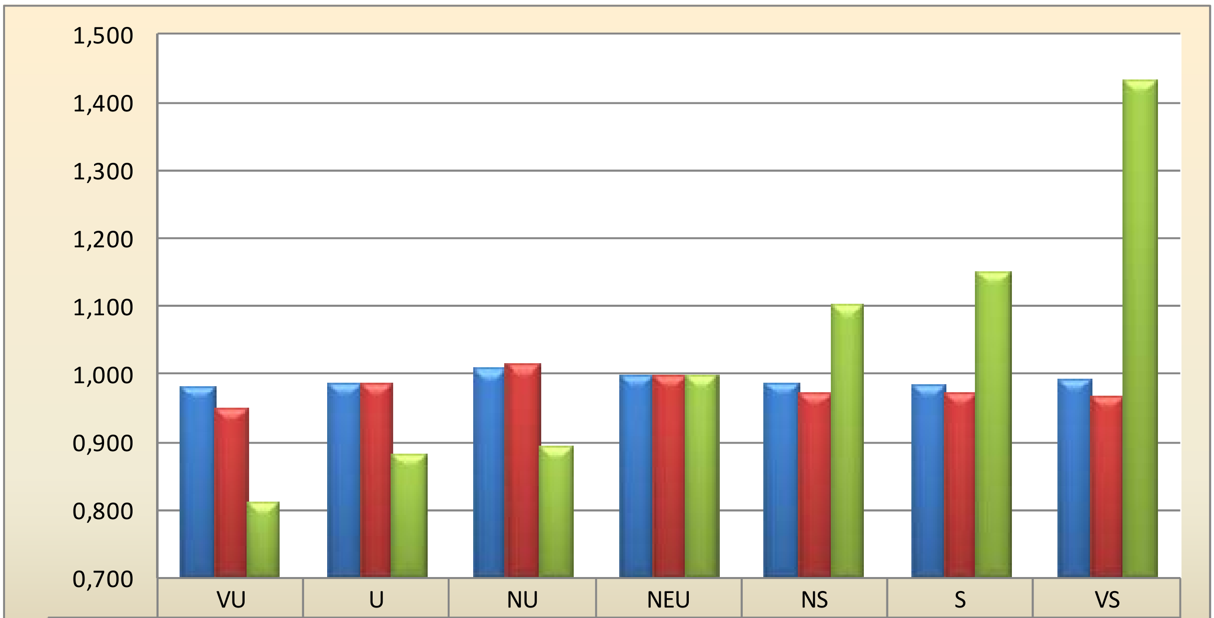
Note: Seven wind profiles and three different turbulence intensities are illustrated. DEL is normalized with the neutral wind profile.



	VU	U	NU	NEU	NS	S	VS
TI 25%	1,003	1,008	1,007	1,000	1,005	0,977	1,010
TI 11%	0,964	0,993	1,008	1,000	0,975	0,971	0,977
TI 0%	0,835	0,899	0,903	1,000	1,083	1,137	1,399

Figure 4.5 TBFx - DEL due to force in x-direction at tower bottom.

Note: Seven wind profiles and three different turbulence intensities are illustrated. DEL is normalized with the neutral wind profile.



	VU	U	NU	NEU	NS	S	VS
TI 25%	0,983	0,988	1,009	1,000	0,988	0,985	0,993
TI 11%	0,950	0,986	1,015	1,000	0,973	0,974	0,967
TI 0%	0,812	0,883	0,893	1,000	1,102	1,152	1,431

Figure 4.6 TBMy - DEL due to bending moment in y-direction at tower bottom.

Note: Seven wind profiles and three different turbulence intensities are illustrated. DEL is normalized with the neutral wind profile.

5 Discussion

In this chapter the damage equivalent load (DEL) will be discussed, to see which wind profile that creates the greatest fatigue. The locations where DEL is calculated are; the blade root, the tower top and the tower bottom. However, only the results at the blade root will be discussed. The coordinate axes are given in Figure 2.3 a) and b). There are a total of seven wind profiles, each of them influenced by three different turbulence intensities (TI):

- TI of 25 %
- TI of 11 %
- TI of 0 %

The seven power law wind profiles are illustrated in Figure 3.2 and the calculated values are presented in Table 8.4 in the Appendix.The seven wind profiles cause different wind profile area that will act over the width of the rotor. A wind profile area is defined as the wind profile integrated over the grid height defined in Sec. 3.4. The wind profile area values are tabulated in Table 3.6. Initially one would expect that the wind profile with the highest wind profile area to provide the greatest DEL. In Table 3.6 and Table 8.4 TI is 0 %. It is worth noting that the speeds vary little from profile to profile. The tiny variation which appears in Table 3.6 produces a pattern in which the very unstable (VU) wind profile gives the least wind effects on the rotor. From this profile the wind effect increases in a stair pattern up to the wind profile very stable (VS), which give the greatest wind effects on the rotor. The wind profile which is expected to give the greatest DEL is therefore the very stable wind profile, but the differences are expected to be small.

In the blue column in Figure 4.2, the result for the bending moment at blade root, RM_Y, for the seven wind profiles are listed, with 25 % TI included. These results do not match the expected result. It seems as if the distribution is relatively random. This relatively randomness may have been caused by the turbulence intensity, or more precisely the size of the turbulence intensity in percent. When the turbulence intensity is equal to 25 %, it causes a standard deviation of $0.25 \cdot U_{10}$. This means that the wind speed can vary ± 25 % about the mean wind speed on average. For the seven wind profiles this gives a variation due to the turbulence in the interval 2.52 – 2.64 m/s, provided that the z-value is 27.55 m. The corresponding interval without turbulence is 10.56 – 10.06 m/s. The variation for z-value of 153.55 m is 3.01 – 2.95 m/s due to the turbulence. The corresponding interval without turbulence is 12.05 – 11.79 m/s. By these numbers it appears clear that the variation due to turbulence is much larger than the distance between the wind profiles. The result is that wind profiles overlap each other. They flow into each other. For this reason it may be difficult to separate the wind profiles, if only running six runs. Thus based on the above it is not possible to conclude which wind profile that provides the greatest damage.

In an attempt to distinguish the wind profiles, the analyses were re-done, but this time with 11% turbulence intensity only. The results are given in the red column in Figure 4.2. It is seen that the red columns create a certain pattern. It forms a roof pattern. Nor does this correspond with the expected pattern, given the fact that the wind profiles, NS, S and VS are exposed to greater wind profile areas than wind profile NEU. The greater the wind profile area, the greater is the expected bending moment RMy/DEL.

There has to be a logical explanation to this roof pattern. The way to explain this may be to distinguish between the expected bending moment BMy and the DEL/RMy. The expected BMy rises from wind profile VU to VS in a stair pattern, in a similar manner as the wind profile area, while the RMy follow a roof pattern. The reason for the three profiles at the right side of NEU having a smaller RMy, may be explained by less fluctuation in the loads.

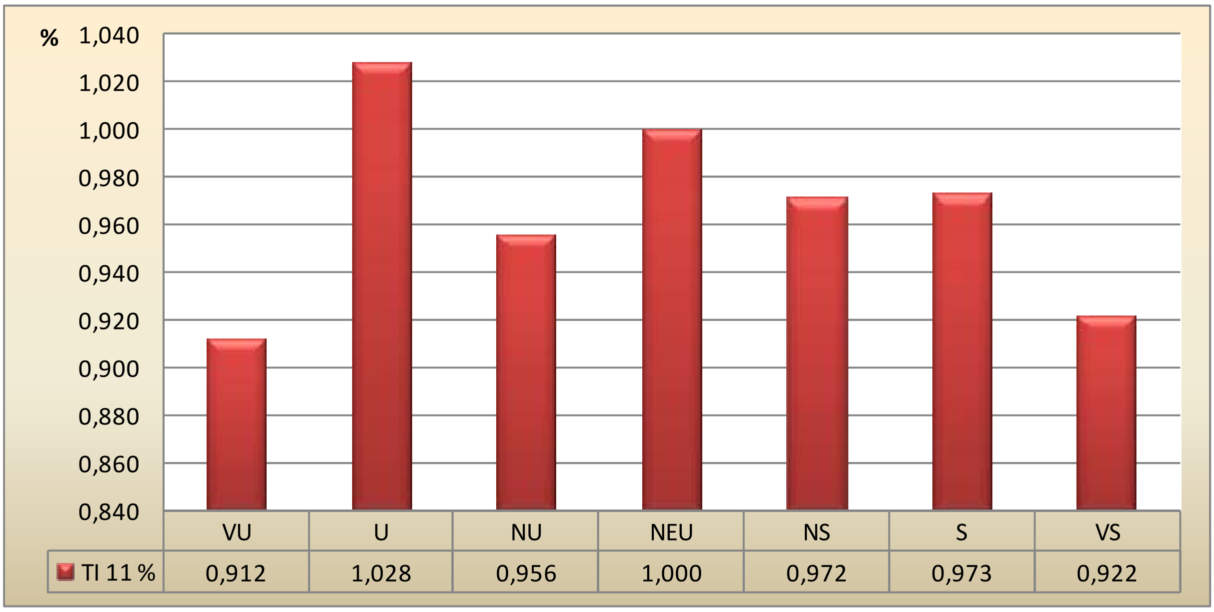
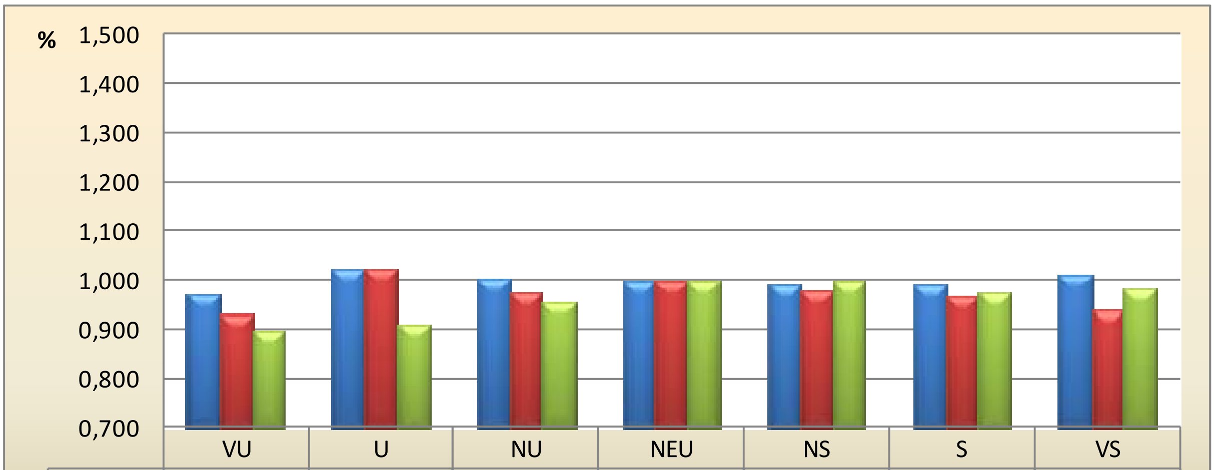


Figure 5.1 Load range of the bending moment in y-direction at blade root, BMy

In Figure 5.1 the load range is given for seven wind profiles, included TI of 11 %. The range is normalized with the neutral wind profile. The range is found by taking the max and min value from the exported data, which is simulated by Fedem. The first 50 seconds of the simulations are not included due to reasons described in Sec. 3.6.

The figure shows that there is less fluctuation for the wind profiles at the right hand side of the wind profile NEU in Figure 5.1. It also shows, by comparing with Figure 4.2, that the shape and the values are quite similar. The next question to ask is why then the expected BMy and the given DEL RMy do not follow the same pattern. The answer may have the same explanation as the case was for TI = 25 %. A TI of 11 % causes, like TI of 25 %, a large deviation from the mean wind speed, for each of the seven wind profiles. For z-value of 27.55 m, the deviation varies between 1.11-1.16 m/s, and for z-value of 153.55 m the variation is between 1.33-1.30 m/s. With the same reasoning as above, the analysis for the seven wind profiles therefore flow into each other, because the distance between the wind profiles is small compared to the turbulence variation.

In order to separate the wind profiles, the turbulence intensity is therefore set to 0 %. The green column in Figure 4.2 represents 0 % TI.



	VU	U	NU	NEU	NS	S	VS
25 % TI	0,971	1,024	1,004	1,000	0,992	0,992	1,009
11 % TI	0,929	1,022	0,973	1,000	0,977	0,967	0,940
0 % TI	0,895	0,910	0,955	1,000	1,000	0,973	0,982

Figure 5.2 RMy - DEL due to bending moment in y-direction at blade root. Not sufficient bins

In Figure 5.2 the bin width from Table 8.19 is used. The results do not match Figure 4.2, where the bin width is different. In Figure 5.2 the bending moment in y-direction at the blade root is shown for the seven wind profiles, with turbulence intensities of 25 %, 11 % and 0 %. The bending moment is normalized with the neutral wind profile.

It can be seen from Figure 5.2 that RMy still follows a roof pattern for turbulence intensity of 0 %. There must be an explanation other than turbulence, which explains why the expected result is not achieved. The density of bins has been reviewed to find an explanation. The bins have a say as to the accuracy of the result. The bin widths used are calculated by taking the range of the neutral wind profile with 25 % TI, and dividing this by 50. This means that this wind profile has 50 bins. For the wind profiles with larger load range in Figure 5.2, this lead to inaccurate results when the same bin number is used due to larger bin width.

Therefore the result in Table 8.19 is rejected. It is considered more correct to use a constant bin width instead of constant bin number. The results in Table 3.9 is derived by dividing the smallest load range of the 91 runs by 50, and the bin width obtained is used for the results of all runs presented in Sec. 4 and in the Appendix. The larger load range will then get more than 50 bins, increasing the accuracy.

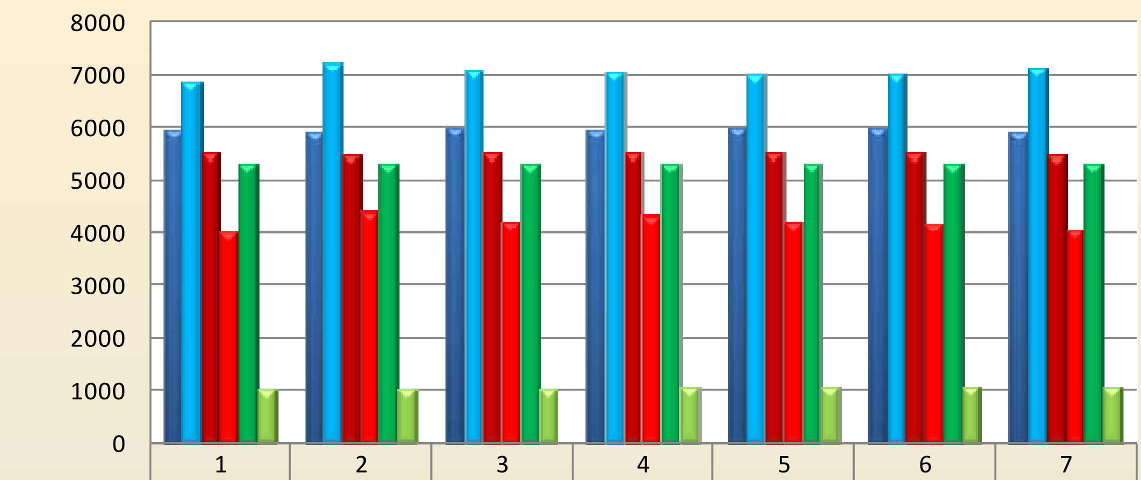
In the green column in Figure 4.2, the wind profiles follow the expected stair pattern. This is almost consistent with the expected result. For the result to be exactly as expected, the wind profile NS should have been slightly larger than NEU, and S should have been slightly larger than NS. The reason why these three wind profiles are alike seems to have something to do with the number of bins used. As Table 3.8 illustrates, if 50 bins is used, these wind profiles are not possible to separate. However this changes when a different number of bins are used. It seems like the DEL-value experiences an alternating convergence. By increasing the number of bins, the alternating range becomes less and less. At 50 bins, one can say that the DEL shown in Table 3.8 is reasonably accurate.

To summarize, the result in the green column in Figure 4.2, coincides with the expected result. To achieve the expected result, the following is done:

- Turbulence is set to 0 %
- A constant bin width is used for all load cases, found by dividing the smallest load range by 50.

With reference to Figure 4.2, the very stable (VS) wind profile causes the greatest DEL. This corresponds to the expected results. The VS profile causes 2 % greater DEL than NEU. The VS wind profile is therefore the most conservative for RMy. However, reservations must be taken for this result due to inaccuracies for the very stable wind profile.

Another important result worth mentioned is how the ratio RMx vs. RMy develops. As a reminder RMx is the bending moment around the x-axis. The x-axis is perpendicular to the rotor plane. RMy is the bending moment around the y-axis. The y-axis is parallell with the rotor plane. See also Figure 2.3. In Figure 5.3 the ratio between these two values are presented.



	1	2	3	4	5	6	7
RMx 25 %	5947	5910	6002	5952	5983	5985	5918
RMy 25 %	6857	7247	7097	7067	7025	7008	7135
RMx 11 %	5512	5478	5485	5508	5488	5505	5468
RMy 11 %	4007	4410	4198	4310	4217	4187	4047
RMx 0 %	5310	5310	5310	5310	5310	5310	5310
RMy 0 %	1020	1040	1040	1070	1070	1070	1090

Figure 5.3 Development of the ratio RMx vs. RMy, by reduction of turbulence intensity

It appears clear that RMy decreases rapidly compared to RMx as the turbulence intensity decreases. The reason for this may be explained by the oscillating movement in the horizontal direction. The oscillation will decrease as the turbulence decrease, as decreasing turbulence means that the wind speed varies less about its mean value.

Figure 5.3 clearly shows that fatigue damage is larger for RMx than for RMy, when TI is chosen to be zero. The RMx is in this case approximately five times larger than RMy for each of the seven wind profiles. The differences in the values of RMx for the seven different wind profiles, are however close to zero. Therefore, all the seven wind profiles provide equal fatigue considering RMx only. Considering RMy instead, the very stable wind profile provides the greatest fatigue.

6 Conclusion

In the thesis seven wind profiles, with turbulence included, have been tested on a 5-MW offshore wind turbine. The turbulence has been set to 25 %, 11 % and 0 %, to investigate the effect that the various wind fields have on the DEL's. It seems as if the result is relatively arbitrary when turbulence is included. The reason may be that the number of runs is too few, due to the fact that the values of the seven wind profile do not vary much, compared to the fluctuation provided by turbulence.

The expected result is achieved when turbulence is set to 0 %. For 0% turbulence the results increases in a stair pattern from the very unstable wind profile to the very stable wind profile. The results are consistent with the wind profile areas, i.e. the greater area the greater DEL (see Table 3.6).

A proposal for future work is to perform even more runs/analyses (increase the number of runs significantly), to ensure that the randomness caused by turbulence is not compromising the confidence of the results.

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8 Appendix

8.1 Wind profiles

Wind profiles	Monin-Obukhov length (Lm0)	Entity	α - exponent	Entity
Very unstable (VU)	-74	[m]	0,105	[-]
Unstable (U)	-142	[m]	0,102	[-]
Near unstable (NU)	-314	[m]	0,100	[-]
Neutral (NEU)	5336	[m]	0,093	[-]
Near stable (NS)	318	[m]	0,086	[-]
Stable (S)	104	[m]	0,082	[-]
Very stable (VS)	28	[m]	0,059	[-]

Stability function (ψ)	
$x = \left(1 - 19{,}3\frac{z}{L_{m0}}\right)^{\frac{1}{4}}$	$\psi_2 = -4{,}8\frac{z}{L_{m0}}$ for $\frac{z}{L_{m0}} \geq 0$
$\psi_1 = 2\ln(1+x) + \ln(1+x^2) - 2tan^{-1}(x)$ for $\frac{z}{L_{m0}} < 0$	

Wind profile parameters	Values	Entities
Height above still sea water level (Z)	Variable	[m]
Roughness length (Z_0)	0,001	[m]
Reference height (H)	90,55	[m]
Reference wind speed [U(H)]	11,4	[m/s]

Function of logarithmic wind profile	Function of power law wind profile
$U(Z) = U(H)\frac{ln\frac{Z}{Z_0} - \psi}{ln\frac{H}{Z_0} - \psi}$	$U(Z) = U(H)\left(\frac{Z}{H}\right)^{\alpha}$

Table 8.1 Collection of wind profile names, abbreviations, parameters and functions

Z	X [VU]	ψ_1 [VU]	X [U]	ψ_1 [U]	X [NU]	ψ_1 [NU]	ψ_2 [NEU]	ψ_2 [NS]	ψ_2 [S]	ψ_2 [VS]
[m]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]
0,1	1,006	0,515	1,003	0,512	1,002	0,510	0,000	-0,002	-0,005	-0,017
5	1,232	0,751	1,138	0,651	1,069	0,579	-0,004	-0,075	-0,231	-0,857
10	1,378	0,911	1,239	0,759	1,127	0,639	-0,009	-0,151	-0,462	-1,714
15	1,489	1,033	1,320	0,847	1,177	0,693	-0,013	-0,226	-0,692	-2,571
20	1,579	1,133	1,389	0,922	1,222	0,740	-0,018	-0,302	-0,923	-3,429
25	1,656	1,218	1,448	0,988	1,262	0,784	-0,022	-0,377	-1,154	-4,286
27,55	1,691	1,257	1,476	1,019	1,281	0,805	-0,025	-0,416	-1,272	-4,723
30	1,724	1,293	1,501	1,047	1,299	0,824	-0,027	-0,453	-1,385	-5,143
35	1,784	1,359	1,549	1,100	1,332	0,861	-0,031	-0,528	-1,615	-6,000
40	1,839	1,419	1,593	1,148	1,364	0,895	-0,036	-0,604	-1,846	-6,857
45	1,889	1,473	1,633	1,193	1,393	0,927	-0,040	-0,679	-2,077	-7,714
50	1,936	1,524	1,671	1,235	1,421	0,958	-0,045	-0,755	-2,308	-8,571
55	1,979	1,570	1,706	1,274	1,447	0,987	-0,049	-0,830	-2,538	-9,429
60	2,020	1,614	1,739	1,310	1,471	1,014	-0,054	-0,906	-2,769	-10,286
65	2,058	1,654	1,771	1,345	1,495	1,040	-0,058	-0,981	-3,000	-11,143
70	2,095	1,693	1,801	1,377	1,517	1,065	-0,063	-1,057	-3,231	-12,000
75	2,129	1,729	1,829	1,408	1,539	1,089	-0,067	-1,132	-3,462	-12,857
80	2,162	1,764	1,856	1,438	1,560	1,112	-0,072	-1,208	-3,692	-13,714
85	2,194	1,796	1,882	1,466	1,580	1,134	-0,076	-1,283	-3,923	-14,571
90	2,224	1,828	1,907	1,493	1,599	1,155	-0,081	-1,358	-4,154	-15,429
90,55	2,227	1,831	1,910	1,496	1,601	1,157	-0,081	-1,367	-4,179	-15,523
95	2,253	1,858	1,931	1,519	1,617	1,175	-0,085	-1,434	-4,385	-16,286
100	2,281	1,886	1,954	1,544	1,635	1,195	-0,090	-1,509	-4,615	-17,143
105	2,308	1,914	1,977	1,568	1,652	1,214	-0,094	-1,585	-4,846	-18,000
110	2,334	1,940	1,998	1,591	1,669	1,233	-0,099	-1,660	-5,077	-18,857
115	2,359	1,966	2,019	1,613	1,685	1,251	-0,103	-1,736	-5,308	-19,714
120	2,384	1,990	2,040	1,635	1,701	1,268	-0,108	-1,811	-5,538	-20,571
125	2,408	2,014	2,059	1,656	1,717	1,285	-0,112	-1,887	-5,769	-21,429
130	2,431	2,037	2,079	1,676	1,732	1,301	-0,117	-1,962	-6,000	-22,286
135	2,453	2,059	2,097	1,695	1,746	1,318	-0,121	-2,038	-6,231	-23,143
140	2,475	2,081	2,115	1,715	1,760	1,333	-0,126	-2,113	-6,462	-24,000
145	2,496	2,102	2,133	1,733	1,774	1,348	-0,130	-2,189	-6,692	-24,857
150	2,517	2,122	2,150	1,751	1,788	1,363	-0,135	-2,264	-6,923	-25,714
153,55	2,531	2,137	2,163	1,764	1,797	1,374	-0,138	-2,318	-7,087	-26,323

Table 8.2 Calculation of the stability parameter, ψ

Z	VU	U	NU	NEU	NS	S	VS
[m]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]
0,1	4,278	4,280	4,281	4,600	4,601	4,602	4,610
5	8,303	8,332	8,352	8,508	8,526	8,564	8,709
10	9,008	9,043	9,069	9,201	9,228	9,285	9,487
15	9,426	9,460	9,488	9,606	9,639	9,707	9,934
20	9,725	9,759	9,787	9,894	9,931	10,004	10,240
25	9,961	9,993	10,020	10,117	10,156	10,233	10,465
27,55	10,064	10,095	10,121	10,214	10,253	10,331	10,559
30	10,156	10,185	10,211	10,299	10,339	10,416	10,639
35	10,322	10,349	10,373	10,453	10,493	10,568	10,778
40	10,468	10,493	10,515	10,587	10,625	10,698	10,890
45	10,598	10,620	10,640	10,704	10,741	10,809	10,983
50	10,715	10,735	10,752	10,809	10,844	10,907	11,061
55	10,823	10,839	10,855	10,904	10,936	10,993	11,127
60	10,921	10,936	10,949	10,991	11,019	11,069	11,184
65	11,013	11,025	11,036	11,071	11,095	11,138	11,232
70	11,098	11,108	11,116	11,144	11,165	11,200	11,275
75	11,178	11,185	11,192	11,213	11,229	11,256	11,312
80	11,254	11,258	11,263	11,277	11,288	11,307	11,344
85	11,325	11,328	11,330	11,337	11,343	11,353	11,372
90	11,393	11,393	11,393	11,394	11,395	11,396	11,397
90,55	11,400	11,400	11,400	11,400	11,400	11,400	11,400
95	11,457	11,455	11,453	11,448	11,443	11,435	11,420
100	11,519	11,515	11,511	11,498	11,488	11,471	11,440
105	11,578	11,571	11,565	11,547	11,530	11,504	11,457
110	11,634	11,626	11,618	11,593	11,570	11,535	11,473
115	11,688	11,678	11,668	11,637	11,607	11,563	11,488
120	11,741	11,728	11,716	11,679	11,643	11,589	11,500
125	11,791	11,777	11,763	11,719	11,676	11,614	11,512
130	11,840	11,823	11,808	11,758	11,708	11,637	11,522
135	11,887	11,868	11,851	11,795	11,738	11,658	11,532
140	11,932	11,912	11,893	11,830	11,767	11,678	11,540
145	11,976	11,954	11,933	11,865	11,795	11,696	11,548
150	12,019	11,995	11,973	11,898	11,821	11,714	11,555
153,55	12,049	12,024	12,000	11,921	11,838	11,725	11,560

Table 8.3 **Calculation of the logarithmic wind profiles**

Z	VU	U	NU	NEU	NS	S	VS
[m]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]
0,1	5,577	5,692	5,771	6,052	6,348	6,523	7,373
5	8,411	8,484	8,533	8,708	8,886	8,990	9,471
10	9,045	9,105	9,146	9,288	9,432	9,516	9,901
15	9,439	9,490	9,524	9,645	9,767	9,837	10,161
20	9,728	9,773	9,802	9,906	10,012	10,072	10,350
25	9,959	9,998	10,023	10,114	10,206	10,258	10,499
27,55	10,061	10,097	10,121	10,206	10,291	10,340	10,564
30	10,151	10,185	10,208	10,287	10,367	10,413	10,622
35	10,317	10,347	10,366	10,435	10,505	10,545	10,727
40	10,463	10,488	10,506	10,566	10,626	10,661	10,819
45	10,593	10,615	10,630	10,682	10,735	10,765	10,901
50	10,711	10,730	10,743	10,787	10,832	10,858	10,975
55	10,819	10,835	10,846	10,883	10,922	10,943	11,042
60	10,918	10,931	10,940	10,972	11,004	11,022	11,104
65	11,010	11,021	11,028	11,054	11,080	11,094	11,161
70	11,096	11,105	11,110	11,130	11,150	11,162	11,214
75	11,177	11,183	11,187	11,202	11,217	11,225	11,263
80	11,253	11,257	11,260	11,269	11,279	11,285	11,310
85	11,325	11,327	11,328	11,333	11,338	11,341	11,354
90	11,393	11,393	11,393	11,394	11,394	11,394	11,396
90,55	11,400	11,400	11,400	11,400	11,400	11,400	11,400
95	11,458	11,456	11,455	11,451	11,447	11,445	11,435
100	11,519	11,516	11,514	11,506	11,498	11,493	11,473
105	11,579	11,573	11,570	11,558	11,546	11,539	11,509
110	11,635	11,629	11,624	11,608	11,592	11,583	11,543
115	11,690	11,681	11,676	11,656	11,637	11,626	11,576
120	11,742	11,732	11,726	11,702	11,679	11,666	11,607
125	11,793	11,781	11,774	11,747	11,721	11,705	11,638
130	11,841	11,828	11,820	11,790	11,760	11,743	11,667
135	11,888	11,874	11,864	11,831	11,798	11,780	11,695
140	11,934	11,918	11,908	11,871	11,835	11,815	11,722
145	11,978	11,961	11,950	11,910	11,871	11,849	11,749
150	12,020	12,002	11,990	11,948	11,906	11,882	11,774
153,55	12,050	12,031	12,018	11,974	11,930	11,905	11,792

Table 8.4 Calculation of the power law wind profiles

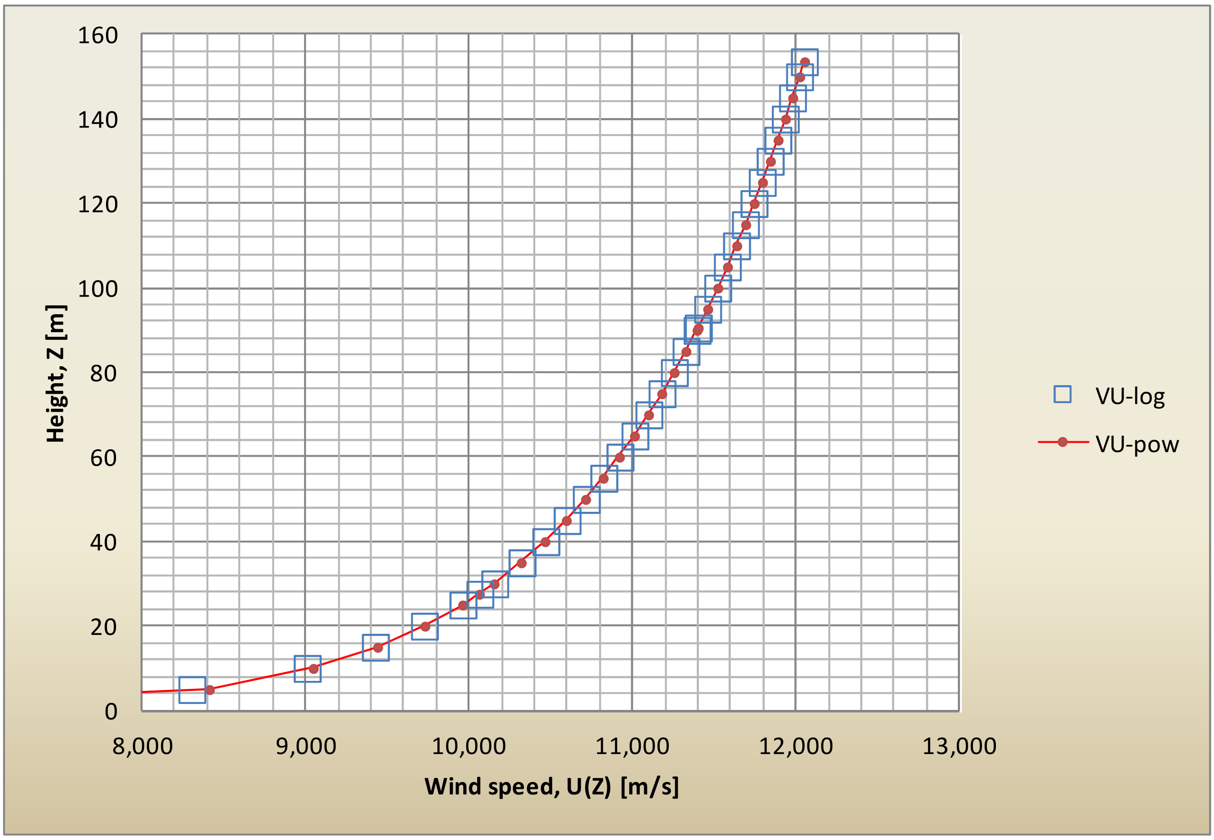


Figure 8.1 Very unstable wind profile – α = 0.105

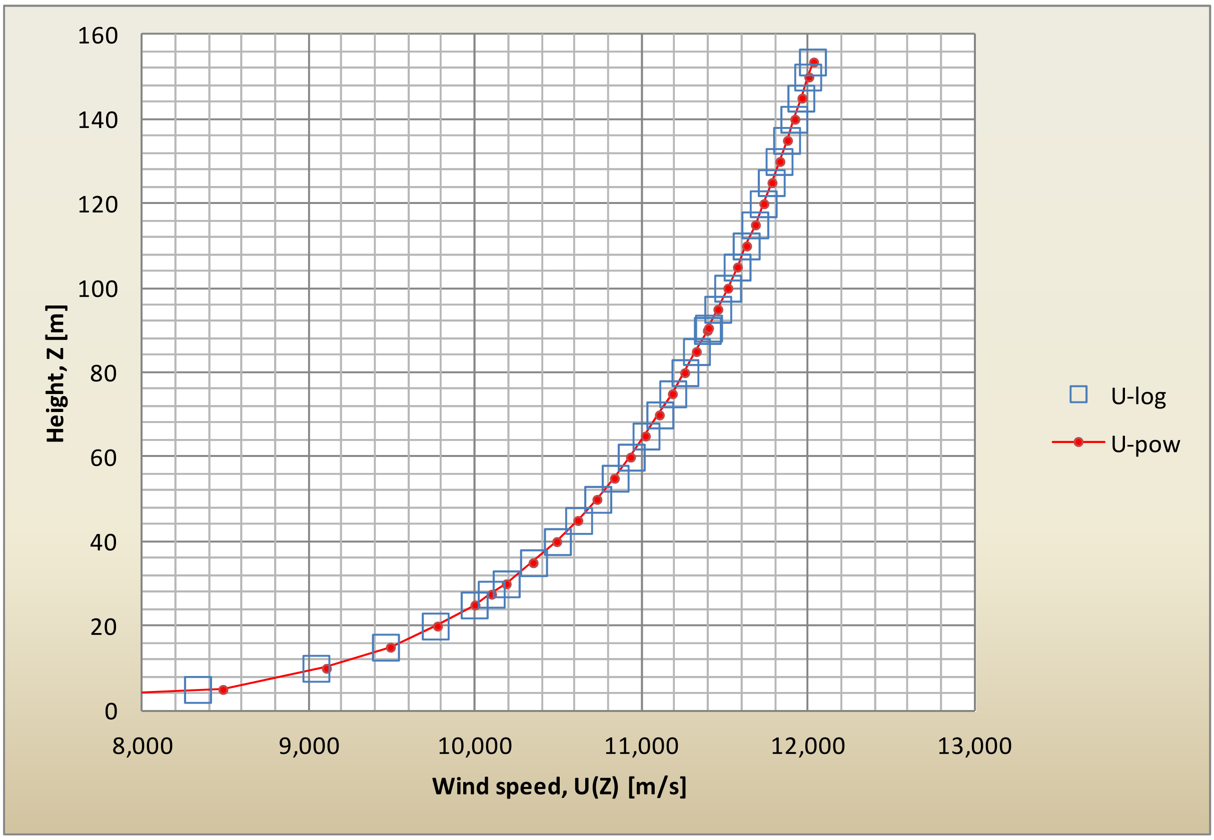


Figure 8.2 Unstable wind profile – α= 0.102

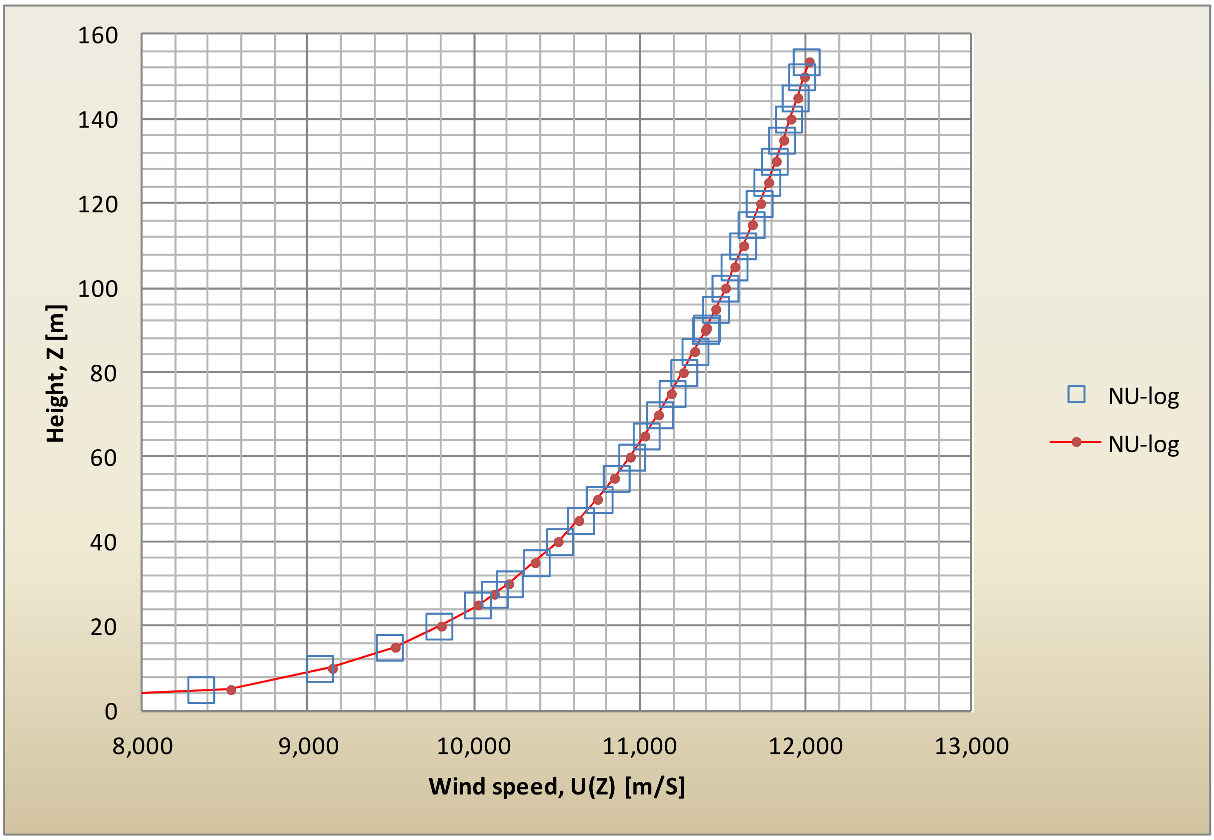


Figure 8.3 Near unstable wind profile – α= 0.100

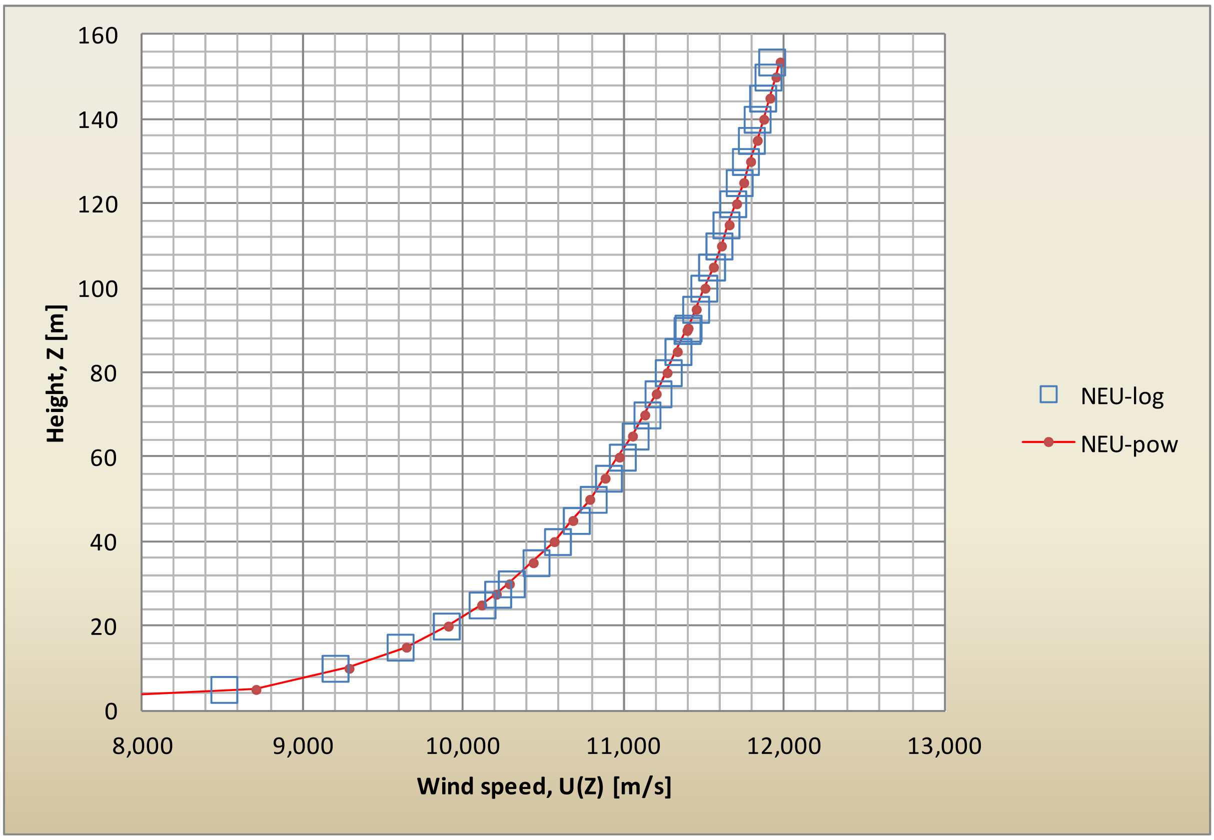


Figure 8.4 Neutral wind profile – α= 0.093

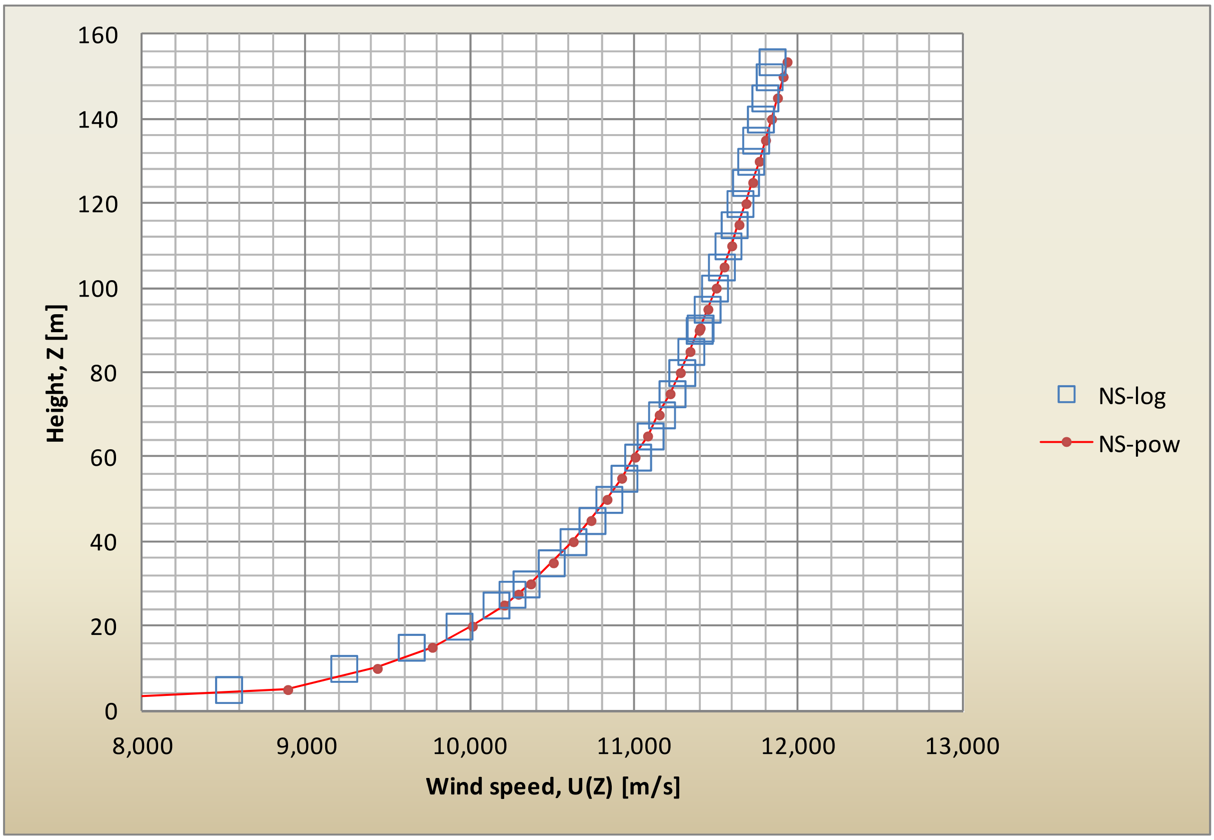


Figure 8.5 **Near stable wind profile – α= 0.086**

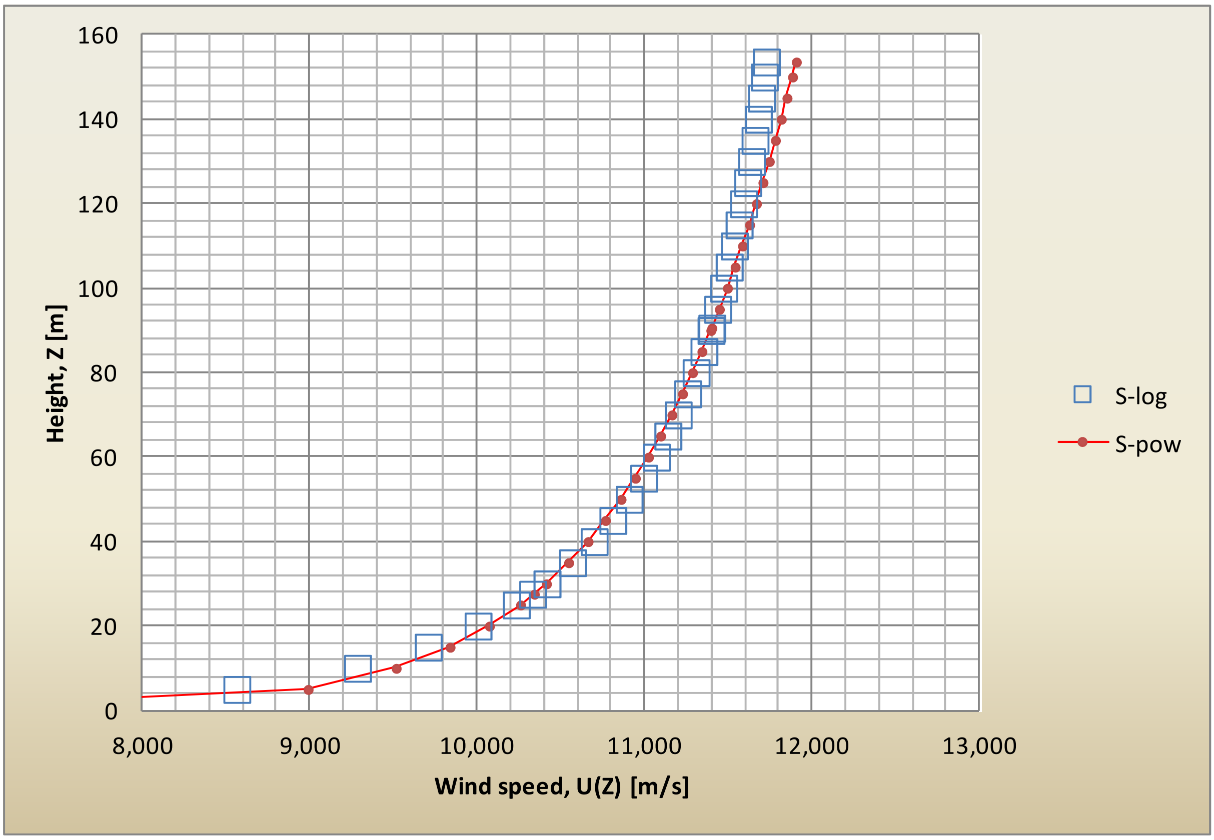


Figure 8.6 **Stable wind profile – α= 0.082**

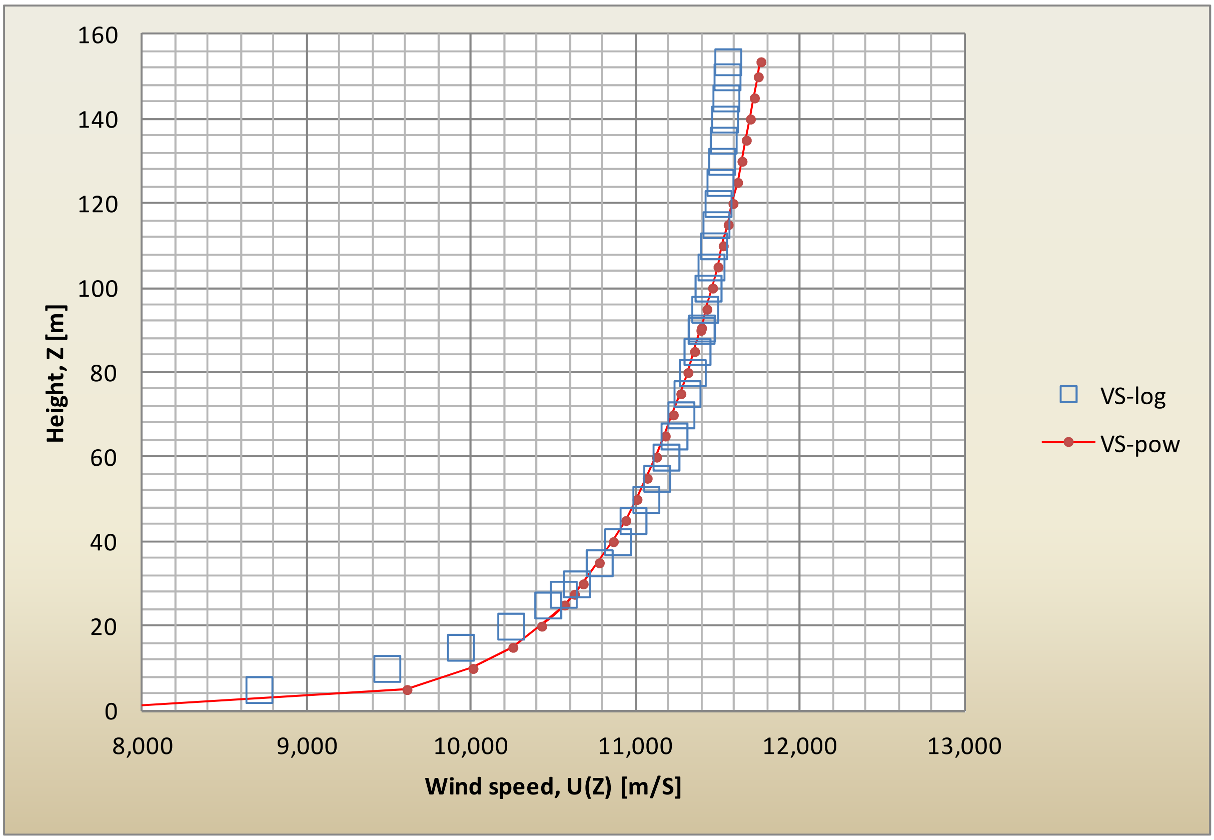


Figure 8.7 **Very stable wind profile – α= 0.059**

8.2 Tables with damage equivalent loads

Run	RFx	RFy	RFz	RMx	RMy	RMz	TTFx	TTFy	TTFz	TTMx	TTMy	TTMz	TBFx	TBFy	TBFz	TBMX	TBMY	TBMZ
VU1	180	273	338	5990	6750	209	205	73	51	736	3000	3460	205	84	54	5610	14300	3490
VU2	172	267	353	5820	6510	164	196	54	53	687	3420	3640	203	61	56	4040	13700	3680
VU3	194	272	357	6000	7370	252	199	55	52	747	3540	3480	204	59	56	4030	14000	3520
VU4	172	272	310	5950	6830	184	196	46	49	642	3040	3350	199	50	53	3450	13600	3390
VU5	174	271	350	6000	6650	268	194	64	52	758	3430	3780	202	73	56	4820	13500	3820
VU6	176	271	375	5920	7030	202	201	59	48	714	2900	3330	208	68	51	4560	13800	3360
Σ/6	**178**	**271**	**347**	**5947**	**6857**	**213**	**199**	**58**	**51**	**714**	**3222**	**3507**	**204**	**66**	**54**	**4418**	**13817**	**3543**

Table 8.5 DEL due to 25 % TI for VU

Run	RFx	RFy	RFz	RMx	RMy	RMz	TTFx	TTFy	TTFz	TTMx	TTMy	TTMz	TBFx	TBFy	TBFz	TBMX	TBMY	TBMZ
U1	189	269	388	5900	7060	158	197	63	48	827	3120	3410	209	72	51	4850	14300	3440
U2	183	271	321	5930	7320	192	197	52	50	654	3330	3610	201	59	53	3890	13800	3650
U3	187	271	379	5970	7220	169	202	59	50	698	3240	3420	211	66	53	4390	14200	3450
U4	172	270	367	5960	6870	240	187	51	51	700	3390	3390	198	56	54	3780	13000	3430
U5	202	267	355	5790	7960	327	197	65	50	706	3120	3540	202	74	53	4920	13900	3580
U6	182	269	376	5910	7050	174	193	52	50	704	3140	3080	206	58	54	3880	14100	3120
Σ/6	**186**	**270**	**364**	**5910**	**7247**	**210**	**196**	**57**	**50**	**715**	**3223**	**3408**	**205**	**64**	**53**	**4285**	**13883**	**3445**

Table 8.6 DEL due to 25 % TI for U

Run	RFx	RFy	RFz	RMx	RMy	RMz	TTFx	TTFy	TTFz	TTMx	TTMy	TTMz	TBFx	TBFy	TBFz	TBMX	TBMY	TBMZ
NU1	192	274	321	5990	7210	215	202	82	48	681	3040	3370	206	98	51	6410	14200	3410
NU2	177	271	336	5920	6960	243	201	51	50	674	3090	3530	201	60	54	3870	14200	3570
NU3	177	275	362	6090	7010	174	192	71	49	765	3340	3520	198	82	52	5460	13600	3550
NU4	183	272	355	6040	6850	242	208	91	54	748	3210	3660	211	106	57	7010	14700	3700
NU5	184	274	310	6040	7170	261	199	74	49	678	3090	3130	207	87	53	5740	14300	3160
NU6	185	271	333	5930	7380	255	197	70	53	764	3230	3600	203	80	56	5410	14100	3640
Σ/6	**183**	**273**	**336**	**6002**	**7097**	**232**	**200**	**73**	**50**	**718**	**3167**	**3468**	**204**	**86**	**54**	**5650**	**14183**	**3505**

Table 8.7 DEL due to 25 % TI for NU

Run	RFx	RFy	RFz	RMx	RMy	RMz	TTFx	TTFy	TTFz	TTMx	TTMy	TTMz	TBFx	TBFy	TBFz	TBMX	TBMY	TBMZ
NEU1	188	269	333	5910	7010	225	210	54	51	683	3160	3580	219	63	55	4140	14900	3620
NEU2	173	273	349	5990	6750	155	192	70	50	654	3200	3690	195	80	54	5320	13300	3730
NEU3	181	274	353	6030	6870	189	184	70	46	733	3200	3350	188	79	49	5280	13000	3400
NEU4	183	272	319	5950	7080	206	220	57	52	679	3020	3280	220	68	56	4420	15300	3320
NEU5	197	271	349	5930	7660	173	206	62	53	679	3300	3470	205	69	57	4700	14600	3500
NEU6	186	270	383	5900	7030	151	184	70	48	803	3250	3090	190	83	51	5470	13200	3120
Σ/6	**185**	**272**	**348**	**5952**	**7067**	**183**	**199**	**64**	**50**	**705**	**3188**	**3410**	**203**	**74**	**53**	**4888**	**14050**	**3448**

Table 8.8 DEL due to 25 % TI for NEU

Run	RFx	RFy	RFz	RMx	RMy	RMz	TTFx	TTFy	TTFz	TTMx	TTMy	TTMz	TBFx	TBFy	TBFz	TBMX	TBMY	TBMZ
NS1	179	272	319	5960	6860	277	198	91	47	710	3270	3320	206	108	50	7180	13900	3350
NS2	188	271	370	6010	7100	212	195	70	50	694	3090	3290	206	81	54	5400	13800	3330
NS3	181	270	403	5940	6940	161	211	57	52	820	3130	3340	214	64	56	4300	14800	3380
NS4	177	267	346	5820	7090	212	181	63	48	676	3390	3660	189	73	51	4800	12800	3700
NS5	189	276	384	6160	7310	249	209	81	47	758	3330	3120	211	93	50	6200	14700	3160
NS6	185	271	353	6010	6850	155	195	78	50	768	3170	3550	197	91	53	6010	13300	3590
Σ/6	**183**	**271**	**363**	**5983**	**7025**	**211**	**198**	**73**	**49**	**738**	**3230**	**3380**	**204**	**85**	**52**	**5648**	**13883**	**3418**

Table 8.9 DEL due to 25 % TI for NS

Run	RFx	RFy	RFz	RMx	RMy	RMz	TTFx	TTFy	TTFz	TTMx	TTMy	TTMz	TBFx	TBFy	TBFz	TBMX	TBMY	TBMZ
S1	180	269	318	5790	7190	228	174	66	51	679	3030	3310	178	75	54	5060	12100	3340
S2	183	277	374	6160	6910	175	206	50	50	744	3120	3420	209	59	53	3870	14700	3460
S3	193	271	373	5960	7200	252	212	66	51	775	3150	3610	216	78	55	5090	14900	3650
S4	171	273	325	6000	6550	149	190	80	50	657	3120	3480	195	93	53	6170	13700	3520
S5	190	273	351	6060	7240	209	201	55	54	680	3310	3730	199	64	57	4270	14100	3760
S6	177	272	380	5940	6960	193	190	56	48	746	3340	3340	192	65	52	4280	13500	3380
Σ/6	**182**	**273**	**354**	**5985**	**7008**	**201**	**196**	**62**	**50**	**714**	**3178**	**3482**	**198**	**72**	**54**	**4790**	**13833**	**3518**

Table 8.10 DEL due to 25 % TI for S

Run	RFx	RFy	RFz	RMx	RMy	RMz	TTFx	TTFy	TTFz	TTMx	TTMy	TTMz	TBFx	TBFy	TBFz	TBMX	TBMY	TBMZ
VS1	200	269	383	5850	7330	159	201	52	49	774	3450	3350	210	59	53	3880	14100	3390
VS2	197	269	352	5930	7460	215	182	61	49	664	3050	3310	187	70	52	4730	13100	3350
VS3	179	270	382	5890	6940	142	196	86	51	763	3200	3510	211	99	54	6600	14000	3540
VS4	186	269	352	5890	7090	190	205	66	50	695	3200	3380	214	76	53	5020	14500	3420
VS5	187	275	342	6090	6980	214	200	75	49	685	3210	3500	205	85	53	5720	14200	3540
VS6	187	269	351	5860	7010	183	199	76	48	727	3020	3160	202	89	52	5890	13800	3200
Σ/6	**189**	**270**	**360**	**5918**	**7135**	**184**	**197**	**69**	**49**	**718**	**3188**	**3368**	**205**	**80**	**53**	**5307**	**13950**	**3407**

Table 8.11 DEL due to 25 % TI for VS

Run	RFx	RFy	RFz	RMx	RMy	RMz	TTFx	TTFy	TTFz	TTMx	TTMy	TTMz	TBFx	TBFy	TBFz	TBMX	TBMY	TBMZ
VU1	105	262	281	5530	4230	132	120	36	25	411	1610	1630	121	42	27	2790	8690	1640
VU2	97	261	282	5500	3760	118	114	36	27	381	1660	1700	112	42	29	2820	7950	1720
VU3	95	262	286	5510	3810	132	115	32	27	397	1630	1700	119	37	29	2470	8150	1720
VU4	105	260	299	5460	4160	110	123	38	26	406	1570	1600	126	44	28	2940	8850	1610
VU5	99	262	278	5530	3990	127	110	35	27	407	1620	1800	109	41	29	2730	7650	1820
VU6	99	262	278	5540	4090	114	110	38	26	409	1540	1640	113	45	28	2970	7780	1650
Σ/6	**100**	**262**	**284**	**5512**	**4007**	**122**	**115**	**36**	**26**	**402**	**1605**	**1678**	**117**	**42**	**28**	**2787**	**8178**	**1693**

Table 8.12 DEL due to 11 % TI for VU

Run	RFx	RFy	RFz	RMx	RMy	RMz	TTFx	TTFy	TTFz	TTMx	TTMy	TTMz	TBFx	TBFy	TBFz	TBMX	TBMY	TBMZ
U1	107	261	306	5480	4440	91	116	39	24	423	1540	1620	112	46	26	3030	8080	1640
U2	104	260	282	5460	4280	94	120	35	25	362	1560	1740	121	41	27	2690	8430	1760
U3	113	261	285	5500	4550	150	117	26	26	361	1560	1630	120	28	28	1900	8210	1650
U4	99	261	281	5470	4170	111	115	21	26	394	1650	1620	116	23	28	1590	8140	1640
U5	114	261	282	5480	4680	158	127	30	25	408	1510	1630	127	35	27	2320	9070	1650
U6	104	261	290	5480	4340	118	123	36	26	380	1560	1450	125	42	28	2800	9000	1470
Σ/6	**107**	**261**	**288**	**5478**	**4410**	**120**	**120**	**31**	**25**	**388**	**1563**	**1615**	**120**	**36**	**27**	**2388**	**8488**	**1635**

Table 8.13 DEL due to 11 % TI for U

Run	RFx	RFy	RFz	RMx	RMy	RMz	TTFx	TTFy	TTFz	TTMx	TTMy	TTMz	TBFx	TBFy	TBFz	TBMX	TBMY	TBMZ
NU1	104	264	279	5560	4130	105	127	33	25	399	1460	1570	127	39	27	2590	9140	1590
NU2	102	261	277	5490	4090	95	116	31	26	371	1460	1680	116	36	28	2370	8300	1700
NU3	100	259	281	5430	4020	143	117	51	26	423	1470	1650	120	60	28	3980	8280	1670
NU4	103	261	279	5490	4070	146	115	40	27	398	1510	1690	115	47	29	3150	8340	1710
NU5	115	262	286	5500	4620	121	128	28	25	406	1540	1540	128	33	27	2180	9150	1560
NU6	105	260	280	5440	4260	132	125	35	27	398	1590	1650	126	41	29	2720	9200	1670
Σ/6	**105**	**261**	**280**	**5485**	**4198**	**124**	**121**	**36**	**26**	**399**	**1505**	**1630**	**122**	**43**	**28**	**2832**	**8735**	**1650**

Table 8.14 DEL due to 11 % TI for NU

Run	RFx	RFy	RFz	RMx	RMy	RMz	TTFx	TTFy	TTFz	TTMx	TTMy	TTMz	TBFx	TBFy	TBFz	TBMX	TBMY	TBMZ
NEU1	111	260	282	5460	4290	156	133	30	28	422	1520	1690	136	36	30	2360	9600	1700
NEU2	101	262	283	5540	4100	121	120	38	25	364	1530	1730	122	45	27	2950	8670	1750
NEU3	108	263	277	5570	4300	125	107	28	24	411	1610	1590	107	33	26	2170	7540	1610
NEU4	109	261	282	5470	4300	171	127	43	26	387	1450	1500	128	50	28	3310	9080	1520
NEU5	118	262	280	5540	4860	112	122	35	26	366	1680	1590	123	40	28	2710	8860	1600
NEU6	103	261	299	5470	4010	149	108	32	25	438	1580	1540	110	38	26	2490	7880	1550
Σ/6	**108**	**262**	**284**	**5508**	**4310**	**139**	**120**	**34**	**25**	**398**	**1562**	**1607**	**121**	**40**	**27**	**2665**	**8605**	**1622**

Table 8.15 DEL due to 11 % TI for NEU

Run	RFx	RFy	RFz	RMx	RMy	RMz	TTFx	TTFy	TTFz	TTMx	TTMy	TTMz	TBFx	TBFy	TBFz	TBMX	TBMY	TBMZ
NS1	102	261	278	5500	4060	150	121	62	24	421	1560	1530	121	74	26	4900	8660	1550
NS2	113	262	284	5520	4530	101	123	41	27	387	1520	1560	125	48	29	3220	8830	1580
NS3	117	260	278	5460	4710	141	116	27	27	405	1720	1680	116	31	29	2090	8240	1700
NS4	104	259	279	5410	4190	143	112	27	25	392	1650	1740	115	31	27	2050	8140	1760
NS5	103	263	286	5550	4070	149	116	29	24	429	1670	1510	117	33	26	2230	8400	1530
NS6	96	261	277	5490	3740	128	113	29	26	406	1540	1670	114	32	28	2150	7960	1680
Σ/6	**106**	**261**	**280**	**5488**	**4217**	**135**	**117**	**36**	**25**	**407**	**1610**	**1615**	**118**	**42**	**27**	**2773**	**8372**	**1633**

Table 8.16 DEL due to 11 % TI for NS

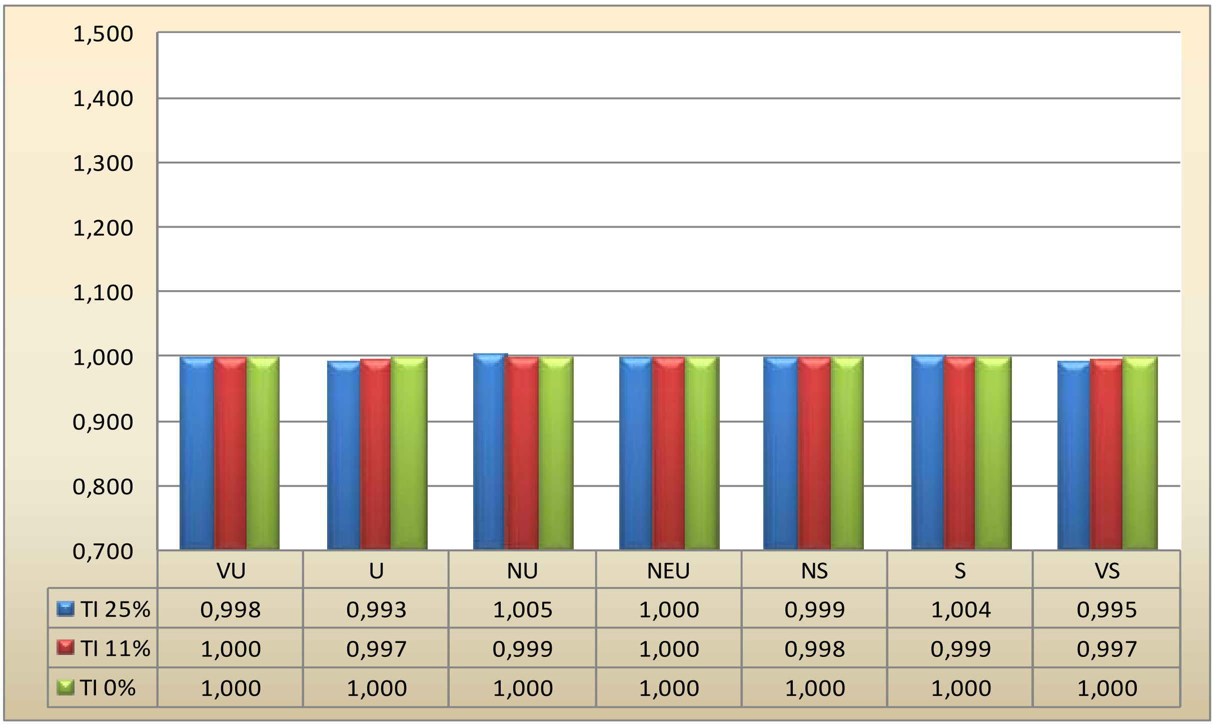
Run	RFx	RFy	RFz	RMx	RMy	RMz	TTFx	TTFy	TTFz	TTMx	TTMy	TTMz	TBFx	TBFy	TBFz	TBMX	TBMY	TBMZ
S1	104	260	276	5440	4160	105	111	42	24	352	1450	1520	110	48	26	3240	7870	1540
S2	105	263	286	5560	4150	97	123	43	26	395	1510	1620	124	51	27	3400	8630	1630
S3	103	261	284	5490	4150	171	124	27	26	423	1470	1700	125	31	28	2070	8850	1720
S4	104	260	279	5480	4160	95	112	32	26	388	1590	1570	113	37	27	2440	7830	1590
S5	103	262	278	5560	4150	118	120	26	27	385	1620	1780	114	30	29	2010	8560	1800
S6	110	262	286	5500	4350	126	117	20	25	410	1640	1600	119	22	27	1450	8560	1620
Σ/6	**105**	**261**	**282**	**5505**	**4187**	**119**	**118**	**32**	**26**	**392**	**1547**	**1632**	**118**	**37**	**27**	**2435**	**8383**	**1650**

Table 8.17 DEL due to 11 % TI for S

Run	RFx	RFy	RFz	RMx	RMy	RMz	TTFx	TTFy	TTFz	TTMx	TTMy	TTMz	TBFx	TBFy	TBFz	TBMX	TBMY	TBMZ
VS1	109	261	288	5470	4110	147	119	25	26	416	1720	1610	118	26	27	1790	8340	1630
VS2	99	259	274	5410	4020	129	107	26	23	378	1530	1570	108	30	25	2000	7800	1590
VS3	103	260	284	5440	4040	105	116	29	25	408	1540	1620	119	33	27	2210	8170	1640
VS4	105	260	280	5460	4140	152	125	50	26	417	1560	1590	128	60	28	3950	8980	1610
VS5	104	263	280	5560	4050	144	118	50	24	414	1560	1660	118	60	26	3940	8370	1680
VS6	102	261	278	5470	3920	116	117	34	25	383	1440	1470	118	40	27	2640	8260	1490
Σ/6	**104**	**261**	**281**	**5468**	**4047**	**132**	**117**	**35**	**25**	**403**	**1558**	**1587**	**118**	**41**	**27**	**2755**	**8320**	**1607**

Table 8.18 DEL due to 11 % TI for VS

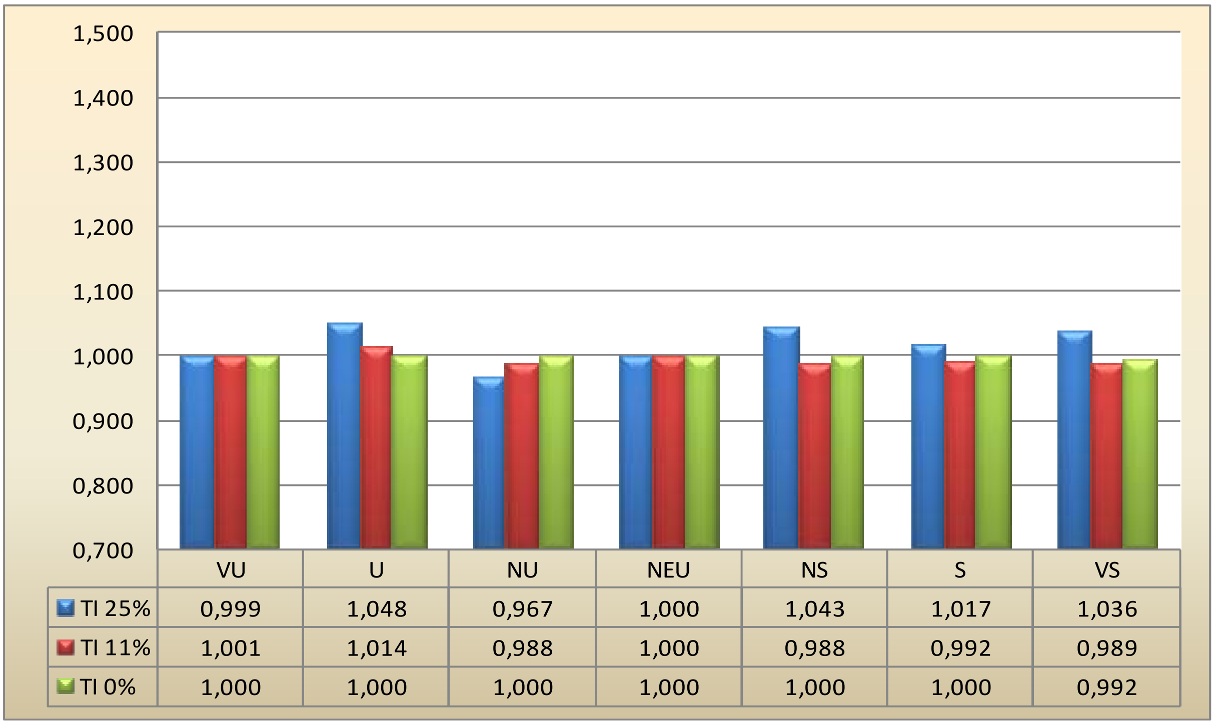
8.3 Graphical presentation of damage equivalent loads



	VU	U	NU	NEU	NS	S	VS
TI 25%	0,998	0,993	1,005	1,000	0,999	1,004	0,995
TI 11%	1,000	0,997	0,999	1,000	0,998	0,999	0,997
TI 0%	1,000	1,000	1,000	1,000	1,000	1,000	1,000

Figure 8.8 RFy – DEL due to force in y-direction at blade root.

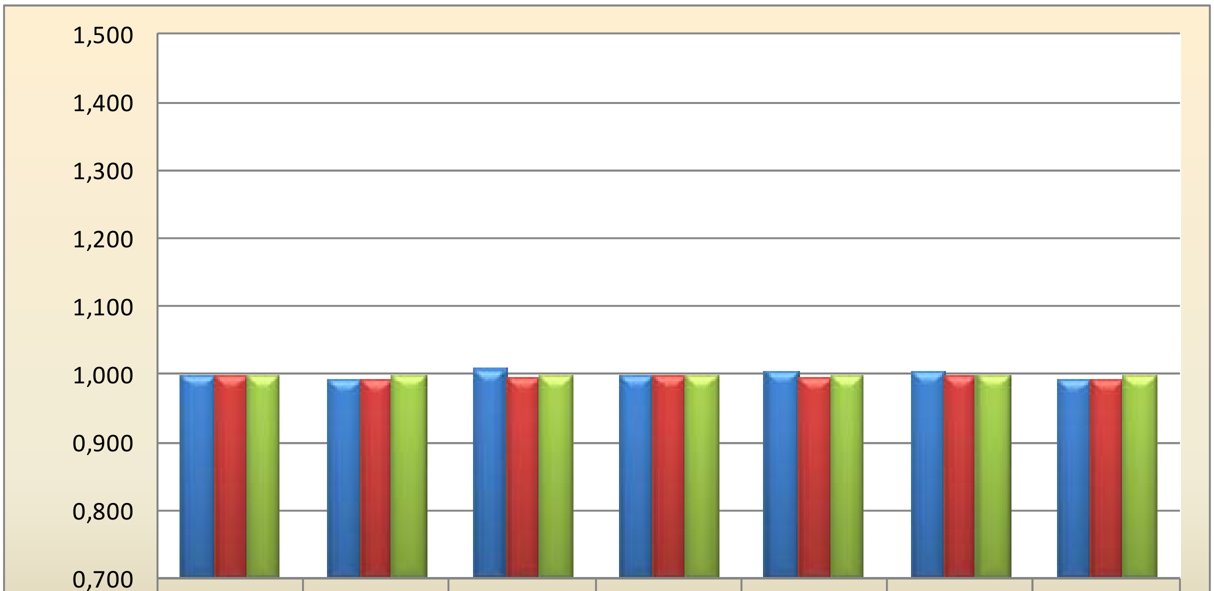
Note: Seven wind profiles and three different turbulence intensities are illustrated. DEL is normalized with the neutral wind profile.



	VU	U	NU	NEU	NS	S	VS
TI 25%	0,999	1,048	0,967	1,000	1,043	1,017	1,036
TI 11%	1,001	1,014	0,988	1,000	0,988	0,992	0,989
TI 0%	1,000	1,000	1,000	1,000	1,000	1,000	0,992

Figure 8.9 RFz – DEL due to force in z-direction at blade root.

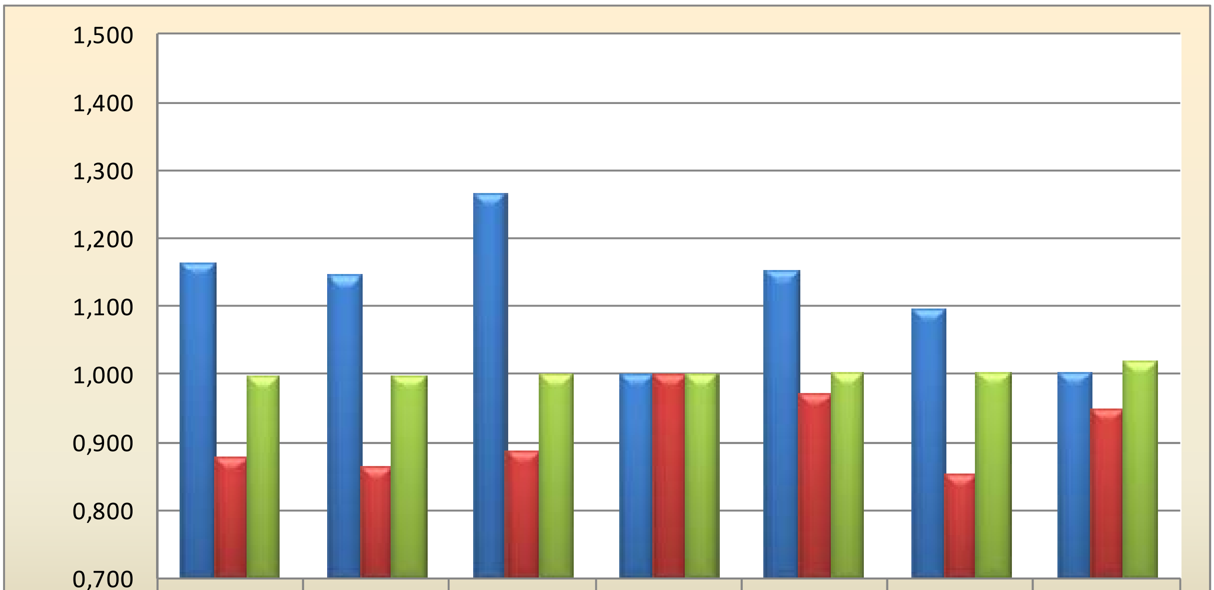
Note: Seven wind profiles and three different turbulence intensities are illustrated. DEL is normalized with the neutral wind profile.



	VU	U	NU	NEU	NS	S	VS
TI 25%	0,999	0,993	1,008	1,000	1,005	1,006	0,994
TI 11%	1,001	0,995	0,996	1,000	0,996	0,999	0,993
TI 0%	1,000	1,000	1,000	1,000	1,000	1,000	1,000

Figure 8.10 RMx – DEL due to bending moment in x-direction at blade root.

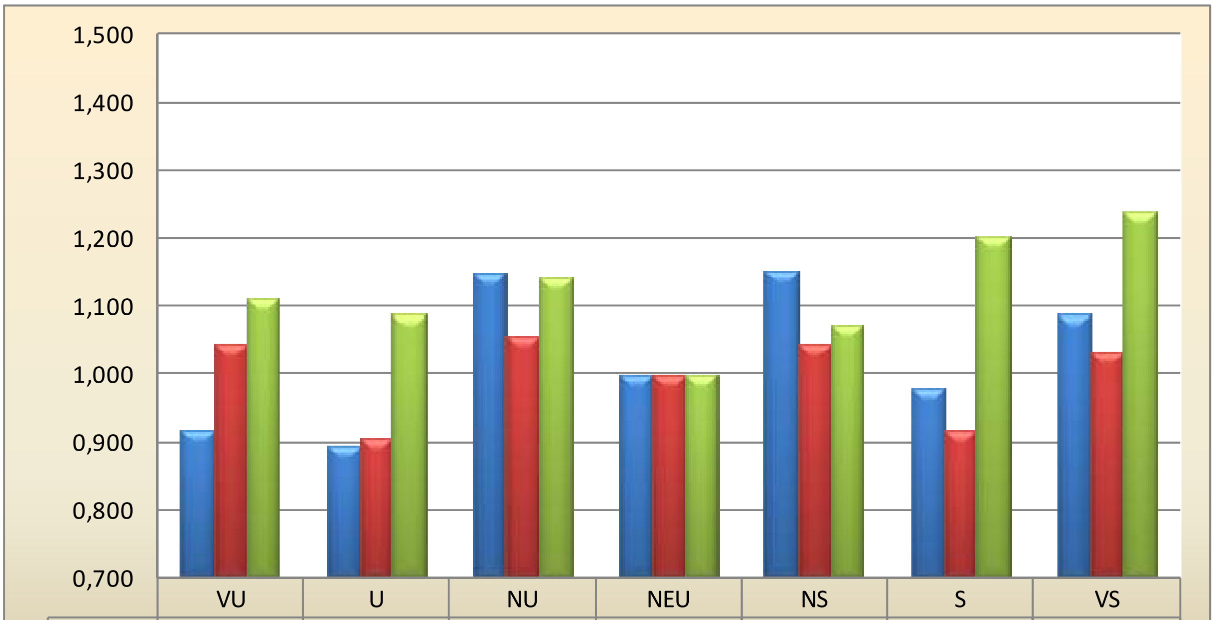
Note: Seven wind profiles and three different turbulence intensities are illustrated. DEL is normalized with the neutral wind profile.



	VU	U	NU	NEU	NS	S	VS
TI 25%	1,164	1,146	1,265	1,000	1,152	1,097	1,004
TI 11%	0,879	0,865	0,890	1,000	0,974	0,853	0,951
TI 0%	0,998	0,998	0,999	1,000	1,001	1,001	1,021

Figure 8.11 RMz – DEL due to bending moment in z-direction at blade root.

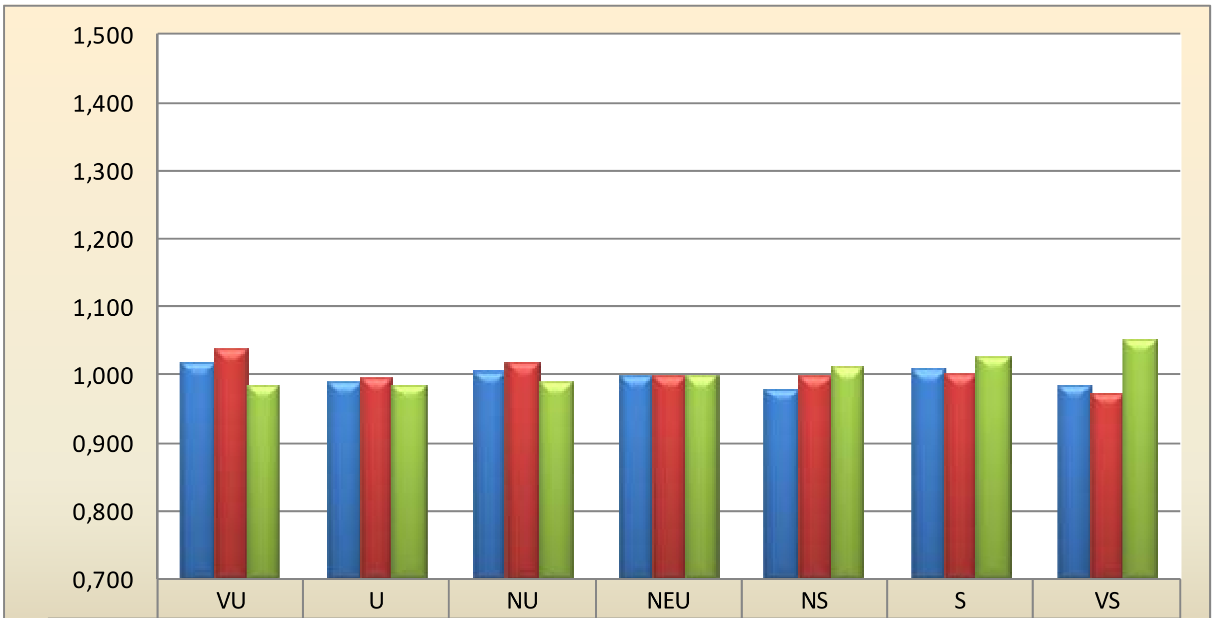
Note: Seven wind profiles and three different turbulence intensities are illustrated. DEL is normalized with the neutral wind profile.



	VU	U	NU	NEU	NS	S	VS
TI 25%	0,917	0,895	1,148	1,000	1,152	0,978	1,088
TI 11%	1,043	0,907	1,055	1,000	1,044	0,918	1,032
TI 0%	1,111	1,088	1,144	1,000	1,072	1,203	1,239

Figure 8.12 TTFy - DEL due to force in y-direction at tower top.

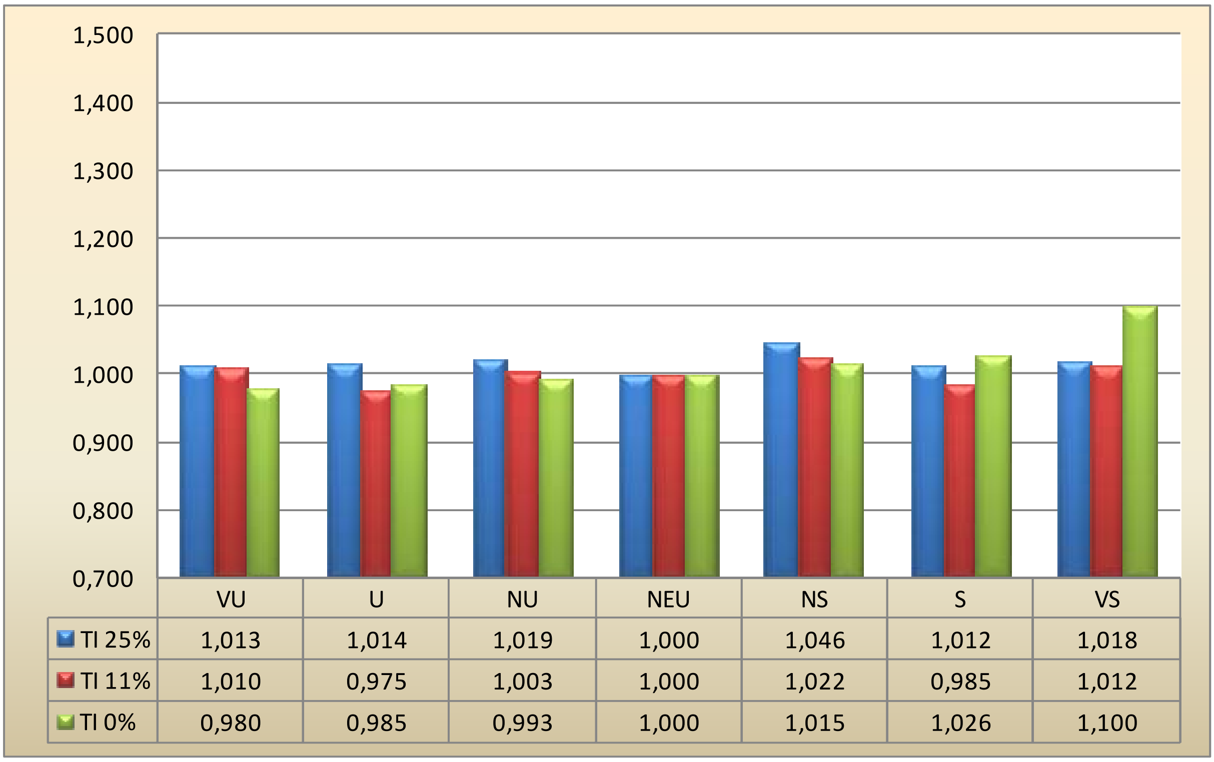
Note: Seven wind profiles and three different turbulence intensities are illustrated. DEL is normalized with the neutral wind profile.



	VU	U	NU	NEU	NS	S	VS
TI 25%	1,017	0,991	1,007	1,000	0,978	1,009	0,985
TI 11%	1,037	0,997	1,016	1,000	0,999	1,003	0,973
TI 0%	0,986	0,984	0,990	1,000	1,010	1,026	1,054

Figure 8.13 TTFz - DEL due to force in z-direction at tower top.

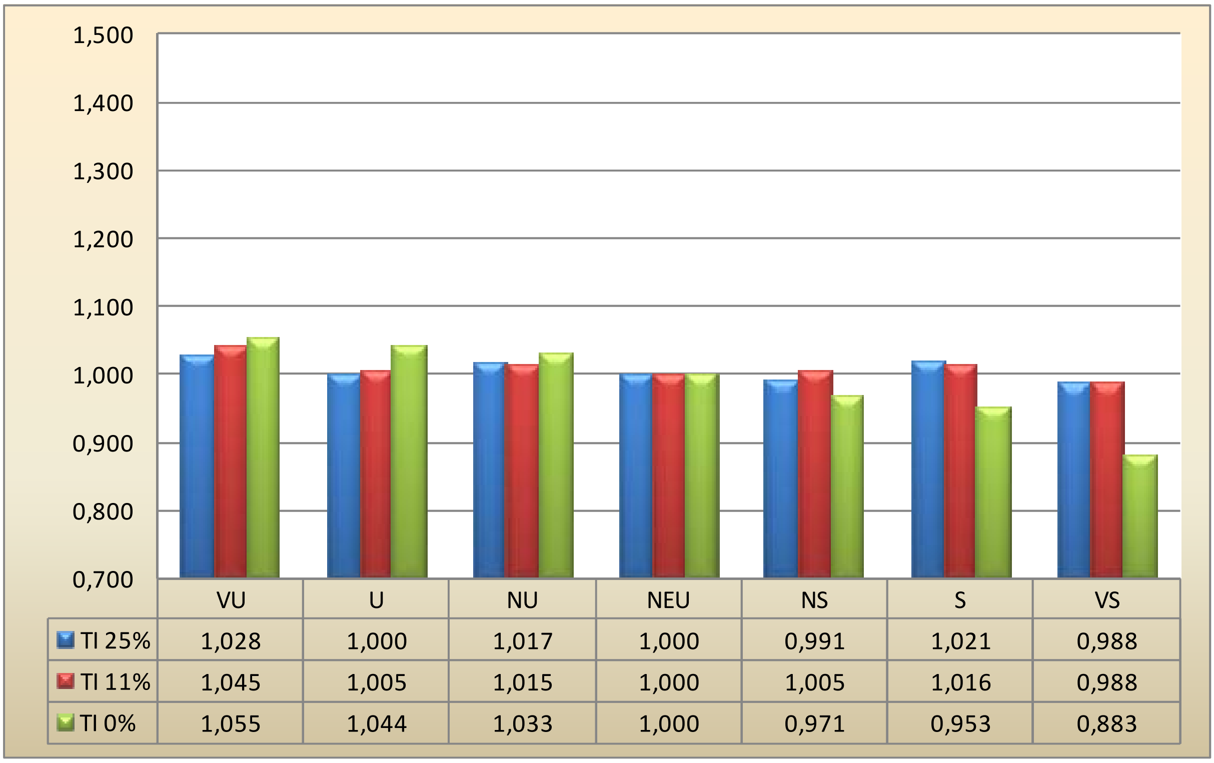
Note: Seven wind profiles and three different turbulence intensities are illustrated. DEL is normalized with the neutral wind profile.



	VU	U	NU	NEU	NS	S	VS
TI 25%	1,013	1,014	1,019	1,000	1,046	1,012	1,018
TI 11%	1,010	0,975	1,003	1,000	1,022	0,985	1,012
TI 0%	0,980	0,985	0,993	1,000	1,015	1,026	1,100

Figure 8.14 TTMx - DEL due to bending moment in x-direction at tower top.

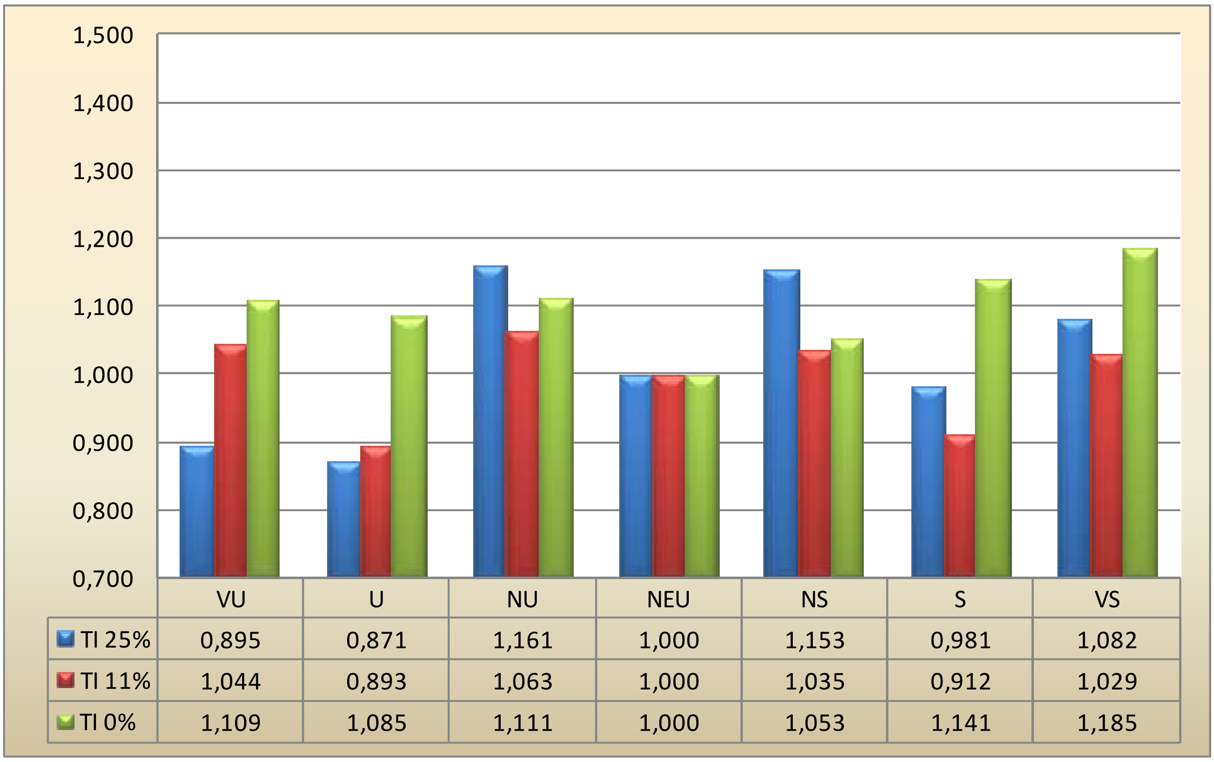
Note: Seven wind profiles and three different turbulence intensities are illustrated. DEL is normalized with the neutral wind profile.



	VU	U	NU	NEU	NS	S	VS
TI 25%	1,028	1,000	1,017	1,000	0,991	1,021	0,988
TI 11%	1,045	1,005	1,015	1,000	1,005	1,016	0,988
TI 0%	1,055	1,044	1,033	1,000	0,971	0,953	0,883

Figure 8.15 TTMz - DEL due to bending moment in z-direction at tower top.

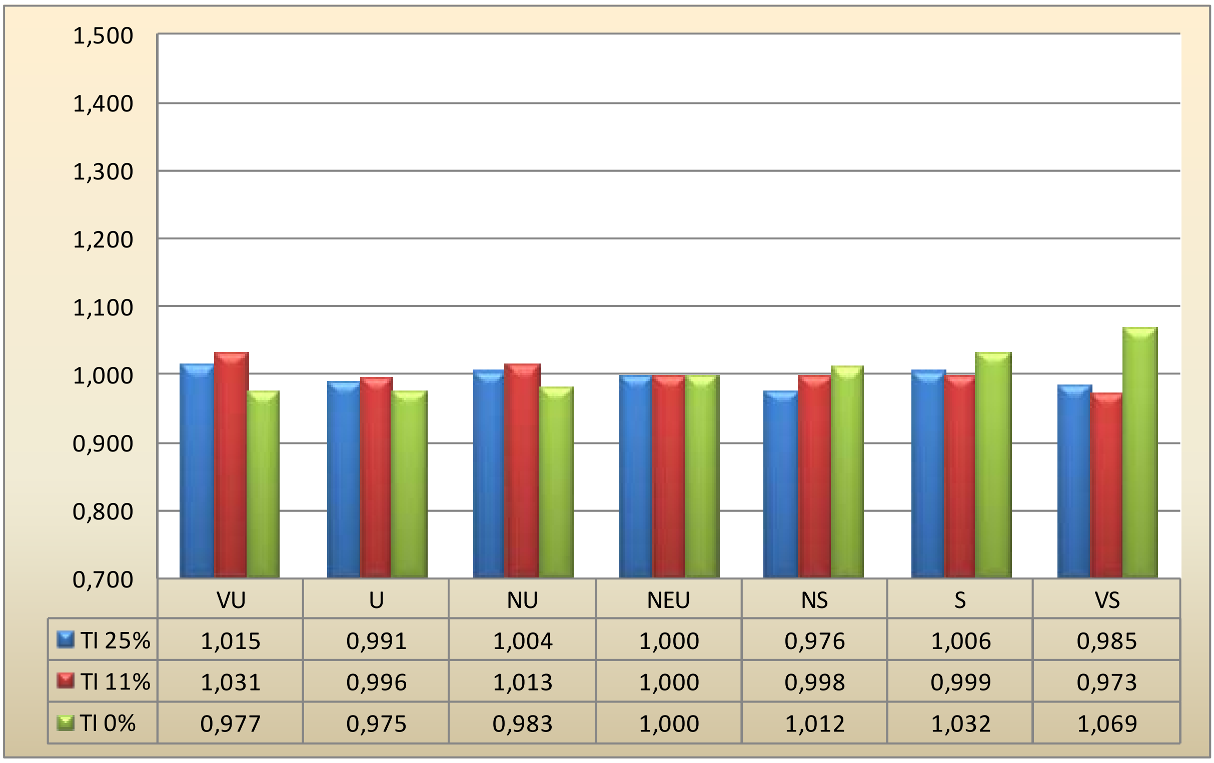
Note: Seven wind profiles and three different turbulence intensities are illustrated. DEL is normalized with the neutral wind profile.



	VU	U	NU	NEU	NS	S	VS
TI 25%	0,895	0,871	1,161	1,000	1,153	0,981	1,082
TI 11%	1,044	0,893	1,063	1,000	1,035	0,912	1,029
TI 0%	1,109	1,085	1,111	1,000	1,053	1,141	1,185

Figure 8.16 TBFy - DEL due to force in y-direction at tower bottom.

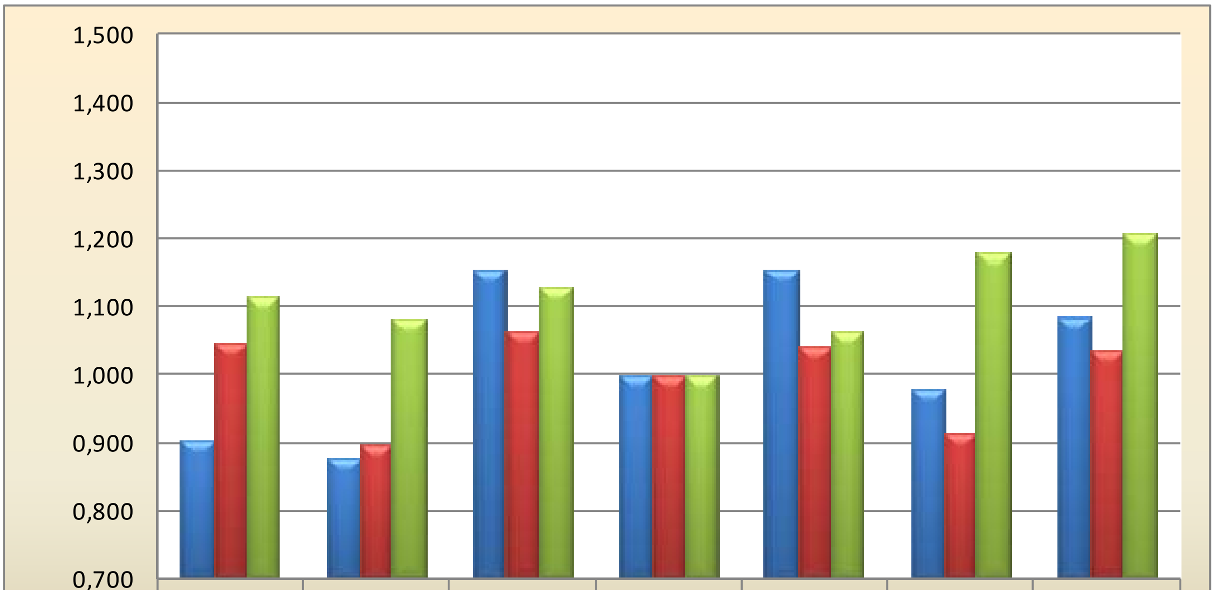
Note: Seven wind profiles and three different turbulence intensities are illustrated. DEL is normalized with the neutral wind profile.



	VU	U	NU	NEU	NS	S	VS
TI 25%	1,015	0,991	1,004	1,000	0,976	1,006	0,985
TI 11%	1,031	0,996	1,013	1,000	0,998	0,999	0,973
TI 0%	0,977	0,975	0,983	1,000	1,012	1,032	1,069

Figure 8.17 TBFz - DEL due to force in z-direction at tower bottom.

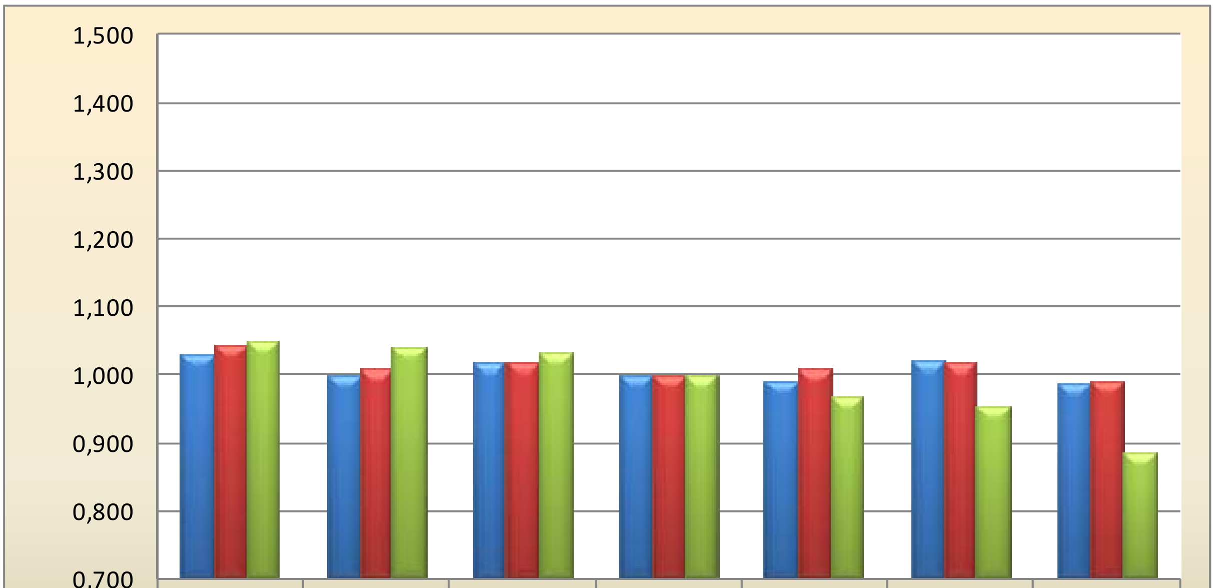
Note: Seven wind profiles and three different turbulence intensities are illustrated. DEL is normalized with the neutral wind profile.



	VU	U	NU	NEU	NS	S	VS
TI 25%	0,904	0,877	1,156	1,000	1,155	0,980	1,086
TI 11%	1,046	0,896	1,063	1,000	1,041	0,914	1,034
TI 0%	1,114	1,082	1,129	1,000	1,063	1,176	1,208

Figure 8.18 TBMx - DEL due to bending moment in x-direction at tower bottom.

Note: Seven wind profiles and three different turbulence intensities are illustrated. DEL is normalized with the neutral wind profile.



	VU	U	NU	NEU	NS	S	VS
TI 25%	1,028	0,999	1,016	1,000	0,991	1,020	0,988
TI 11%	1,044	1,008	1,017	1,000	1,007	1,017	0,991
TI 0%	1,050	1,040	1,032	1,000	0,968	0,953	0,885

Figure 8.19 TBMz - DEL due to bending moment in z-direction at tower bottom.

Note: Seven wind profiles and three different turbulence intensities are illustrated. DEL is normalized with the neutral wind profile.

8.4 Bin widths

Loads	Bin width	Loads	Bin width
RFx	8	**TTMx**	84
RFy	9	**TTMy**	302
RFz	15	**TTMz**	345
RMx	208	**TBFx**	18
RMy	295	**TBFy**	6
RMz	10	**TBFz**	4
TTFx	18	**TBMx**	378
TTFy	5	**TBMy**	1166
TTFz	4	**TBMz**	348

Table 8.19 Bin widths found by dividing the largest neutral load range by 50

8.5 Turbsim input file

```
TurbSim Input File. Valid for TurbSim v1.50, 25-Sep-2009. Input File for Certification Test.

---------Runtime Options-----------------------------------

578825          RandSeed1       - First random seed  (-2147483648 to 2147483647)

321216          RandSeed2       - Second random seed (-2147483648 to 2147483647) for intrinsic pRNG, or an alternative pRNG: "RanLux" or "RNSNLW"

False           WrBHHTP         - Output hub-height turbulence parameters in GenPro-binary form?  (Generates RootName.bin)

True            WrFHHTP         - Output hub-height turbulence parameters in formatted form?  (Generates RootName.dat)

False           WrADHH          - Output hub-height time-series data in AeroDyn form?  (Generates RootName.hh)

True            WrADFF          - Output full-field time-series data in TurbSim/AeroDyn form? (Generates RootName.bts)

False           WrBLFF          - Output full-field time-series data in BLADED/AeroDyn form?  (Generates RootName.wnd)

False           WrADTWR         - Output tower time-series data? (Generates RootName.twr)

False           WrFMTFF         - Output full-field time-series data in formatted (readable) form?  (Generates RootName.u, RootName.v, RootName.w)

True            WrACT           - Output coherent turbulence time steps in AeroDyn form? (Generates RootName.cts)

True            Clockwise       - Clockwise rotation looking downwind? (used only for full-field binary files - not necessary for AeroDyn)

 0              ScaleIEC        - Scale IEC turbulence models to exact target standard deviation? [0=no additional scaling; 1=use hub scale uniformly; 2=use individual scales]

--------Turbine/Model Specifications----------------------

10               NumGrid_Z       - Vertical grid-point matrix dimension

10               NumGrid_Y       - Horizontal grid-point matrix dimension

0.025            TimeStep        - Time step [seconds]

1050.0          AnalysisTime    - Length of analysis time series [seconds] (program will add time if necessary: AnalysisTime = MAX(AnalysisTime, UsableTime+GridWidth/MeanHHWS) )

850.0           UsableTime      - Usable length of output time series [seconds] (program will add GridWidth/MeanHHWS seconds)

90.55           HubHt           - Hub height [m] (should be > 0.5*GridHeight)

130.00           GridHeight      - Grid height [m]

130.00           GridWidth       - Grid width [m] (should be >= 2*(RotorRadius+ShaftLength))

 0              VFlowAng        - Vertical mean flow (uptilt) angle [degrees]

 0              HFlowAng        - Horizontal mean flow (skew) angle [degrees]

--------Meteorological Boundary Conditions-------------------

"IECKAI"        TurbModel       - Turbulence model ("IECKAI"=Kaimal, "IECVKM"=von Karman, "GP_LLJ", "NWTCUP", "SMOOTH", "WF_UPW", "WF_07D", "WF_14D", or "NONE")

3               IECstandard     - Number of IEC 61400-x standard (x=1,2, or 3 with optional 61400-1 edition number (i.e. "1-Ed2") )

0.000000001              IECturbc        - IEC turbulence characteristic ("A", "B", "C" or the turbulence intensity in percent) ("KHTEST" option with NWTCUP, not used for other models)

NTM             IEC_WindType    - IEC turbulence type ("NTM"=normal, "xETM"=extreme turbulence, "xEWM1"=extreme 1-year wind, "xEWM50"=extreme 50-year wind, where x=wind turbine class 1, 2, or 3)

default         ETMc            - IEC ETM "c" parameter [m/s] (or "default")

PL              WindProfileType - Wind profile type ("JET"=Low-level jet,"LOG"=Logarithmic,"PL"=Power law, "IEC"=PL on rotor & LOG elsewhere, or "default")

90.55            RefHt           - Height of the reference wind speed [m]

11.4            URef            - Mean (total) wind speed at the reference height [m/s]

350             ZJetMax         - Jet height [m] (used only for JET wind profile, valid 70-490 m)

0.082         PLExp           - Power law exponent  (or "default")
```

```
default          Z0               - Surface roughness length [m] (or "default")

--------Non-IEC Meteorological Boundary Conditions------------

default          Latitude         - Site latitude [degrees] (or "default")

0.05             RICH_NO          - Gradient Richardson number

default          UStar            - Friction or shear velocity [m/s] (or "default")

default          ZI               - Mixing layer depth [m] (or "default")

default          PC_UW            - Mean hub u'w' Reynolds stress (or "default" or "none")

default          PC_UV            - Mean hub u'v' Reynolds stress (or "default" or "none")

default          PC_VW            - Mean hub v'w' Reynolds stress (or "default" or "none")

default          IncDec1          - u-component coherence parameters (e.g. "10.0  0.3e-3" in quotes) (or "default")

default          IncDec2          - v-component coherence parameters (e.g. "10.0  0.3e-3" in quotes) (or "default")

default          IncDec3          - w-component coherence parameters (e.g. "10.0  0.3e-3" in quotes) (or "default")

default          CohExp           - Coherence exponent (or "default")

--------Coherent Turbulence Scaling Parameters-------------------

".\EventData"    CTEventPath      - Name of the path where event data files are located

LES              CTEventFile      - Type of event files ("random", "les" or "dns")

true             Randomize        - Randomize disturbance scale and location? (true/false)

1.0              DistScl          - Disturbance scale (ratio of dataset height to rotor disk).

0.5              CTLy             - Fractional location of tower centerline from right (looking downwind) to left side of the
dataset.

0.5              CTLz             - Fractional location of hub height from the bottom of the dataset.

30.0             CTStartTime      - Minimum start time for coherent structures in RootName.cts [seconds]

==================================================

NOTE: Do not add or remove any lines in this file!

==================================================
```

8.6 Mlife text file

```
-----  MLife version 1.0 Input File  -------------------------------------------
Binned (+Names, -Chans, -CC, -TSp, +Stats, +SwT, -SwX, -SF, -EE, -Bins, -Bp, -PDF, -PDFp, -PSD, -PSDp, -PSDtxt, -PSDxls, +F,
+FBR, +FBM, +DEL, -CF, -FwDELt, +FwDELx, -FwRFt, +FwRFx, +FpBC, -FpPE, -FpCC, -FpRM, +TbDEL, +Multi).
-----  Job Options  ------------------------------------------------------------
false         EchoInp            Echo input to <rootname>.echo as this file is being read.
false              StrNames           Use channel names following a "$" instead of numbers when specifying channels in this
input file.
false         OutData            Output modified data array after scaling and calculated channels. (currently unavailable)
"%10.2e"          RealFmt            Format for outputting floating-point values.
"U"          AggRoot            Root name for aggregate output files.
-----  Input-Data Layout  ------------------------------------------------------
0                 TitleLine          The row with the file title on it (zero if no title is available).
7                 NamesLine          The row with the channel names on it (zero if no names are available or are specified
below).
0                 UnitsLine          The row with the channel units on it (zero if no units are available or are specified
below).
1008                 FirstDataLine      The first row of data.
22                NumChans           The number of channels in each input file.
ChanTitle    ChanUnits    Scale  Offset     NumCols rows of data follow.  Title and units strings must be 10 characters or
less.
"Description"    "s"             1.0           0.0
"WindVxi"       "m/s"          1.0           0.0
"WindVyi"       "m/s"          1.0           0.0
"WindVzi"       "m/s"          1.0           0.0
"RootFxc1"      "kN"           1.0           0.0
"RootFyc1"      "kN"           1.0           0.0
"RootFzc1"      "kN"           1.0           0.0
"RootMxc1"      "kNm"          1.0           0.0
"RootMyc1"      "kNm"          1.0           0.0
"RootMzc1"      "kNm"          1.0           0.0
"YawBrFxp"      "kN"           1.0           0.0
"YawBrFyp"      "kN"           1.0           0.0
"YawBrFzp"      "kN"           1.0           0.0
"YawBrMxp"      "kNm"          1.0           0.0
"YawBrMyp"      "kNm"          1.0           0.0
"YawBrMzp"      "kNm"          1.0           0.0
"BottomFx"      "kN"           1.0           0.0
"BottomFy"      "kN"           1.0           0.0
"BottomFz"      "kN"           1.0           0.0
"BottomMx"      "kNm"          1.0           0.0
"BottomMy"      "kNm"          1.0           0.0
"BottomMz"      "kNm"          1.0           0.0
-----  Calculated Channels  ----------------------------------------------------
0                 NumCChan           The number calculated channels to generate.
1234567890        Seed               The integer seed for the random number generator (-2,147,483,648 to 2,147,483,647)
Col_Title   Units    Equation        Put each field in quotes.  Titles and units are limited to 10 characters.  NumCChan rows
of data follow.
-----  Time and Wind Speed  ----------------------------------------------------
1            TimeChan          The channel containing time.
2        WSChan            The primary wind-speed channel (used for mean wind speed and turbulence intensity, 0 for none)
-----  Statistics and Extreme Events  ------------------------------------------
false         DoStats            Generate statistics of all the channels.
true          WrStatsTxt         Write the stats to a text file?
false         WrStatsXLS         Write the stats to an Excel file?
0                 NumSFChans         Number of channels that will have summary statistics generated for them.
1            SFChans            List of channels that will have summary statistics generated for them.  Must number
NumSFChans.
-----  Fatigue  ----------------------------------------------------------------
18                 nFatigueChannels   The number of fatigue channels.  Next six lines ignored if zero.
0.0               FiltRatio          The fraction of the maximum range of each channel used as a cutoff range for the
racetrack filter.  Use zero for no filter.
630720000         DesignLife         Number of seconds in the design lifetime (20 years = 630720000 seconds).
true              BinCycles          Bin the rainflow cycles?
0.5               UCMult             Multiplier for binning unclosed cycles.  (0 discards, 1 counts as a full cycle)
true               DoSimpDELs         Compute short-term (file-based) damage-equivalent loads?
false              DoLife             Do lifetime-related calculations?
10                WeibullMeanWS      Weibull-average wind speed.
2                 WeibullShapeFactor Shape parameter for Weibull distribution.  2 = Rayleigh distribution
3                 WSmin              Starting value for the wind-speed bins for the Weibull distribution.
BW                WSBinFlag          BN = number of bins specified or BW = bin width specified
6                 WSBinVal           Number of bins or the width of the wind-speed bins for the Weibull distribution.
true          WrDELsTxt          Write DELs to plain-text files?
false         WrDELsXLS          Write DELs to an Excel workbook?
false         WrLifeTxt          Write lifetime results to plain-text files?
false         WrLifeXLS          Write lifetime results to an Excel workbook?
10                EquivFreq          The frequency of the damage equivalent load (Hz)
true              DEL_AsRange        true = report DELs as a range value,  false = report as a one-sided amplitude
Channel#  NSlopes  SNslopeLst      BinFlag  BinWidth/Number  TypeLMF     LUlt    BinWidth not used when BinCycles is false.
nFatigueChannels rows of data follow.  LUlt >> LMF
5           1      12          BW                0.7          161           9000
6           1      12          BW                7.1           33           9000
7           1      12          BW                7.0          494           9000
8           1      12          BW              145.5          161         152000
9           1      12          BW               32.8           33         152000
10          1      12          BW                2.4          494         152000
11          1       5          BW                1.6          161          57000
12          1       5          BW                0.2           33          57000
13          1       5          BW                0.3          494          57000
14          1       5          BW                2.6          161         707000
15          1       5          BW               16.9           33         707000
16          1       5          BW               10.5          494         707000
17          1       5          BW                1.6          161          57000
18          1       5          BW                0.3           33          57000
19          1       5          BW                0.3          494          57000
20          1       5          BW               18.8          161         707000
21          1       5          BW              104.7           33         707000
22          1       5          BW               10.7          494         707000
1                 NumDELGroups       Number of DEL groups.  DEL tables are organized according to groups.
NChannels      ChannelList
18               1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
-----  Input Files  ------------------------------------------------------------
6                NumFiles          The number of input files to read.
"U1.out"
"U2.out"
"U3.out"
"U4.out"
"U5.out"
"U6.out"
==EOF==                            DO NOT REMOVE OR CHANGE.  MUST COME JUST AFTER LAST LINE OF VALID INPUT.
```